FINAL TECHNICAL REPORT

PROJECT TITLE

DESIGN AND CONSTRUCTION OF COAL/BIOMASS TO LIQUIDS (CBTL) PROCESS DEVELOPMENT UNIT (PDU) AT THE UNIVERSITY OF KENTUCKY CENTER FOR APPLIED ENERGY RESEARCH (CAER)

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DISCLAIMER

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Coal gasification, gas clean-up processes and coal/biomass-to-chemicals represent fruitful fields of research and investigation for UK's Center for Applied Energy Research – and the facility made possible through this grant will be an important syngas production facility for a variety of future and complimentary research. This project benefited greatly from CAER's strong collaborations in China. The authors wish to acknowledge the outstanding contribution of GONG, Xin, YU Guangsuo, WANG Fuchen, GUO Qinghua, XU Jianliang and GONG Yan of the China Ministry of Education's Key Laboratory of Coal Gasification, East China University of Science and Technology; WANG Qiuming and TAO Li of the China Electronics and Engineering Design Institute, and REN Xiangkun of Beijing Baota Sanju Energy Science & Technology Co. Ltd. The authors also wish to acknowledge our North American contributors as well, including David Beckman, Leisl Dukhedin-Lalla and Ravine Dave of ZETON, Inc., Burlington, Canada, and CAER's research and facilities staff, Burt Davis, Gary Jacobs, Dennis Sparks, Will Shafer, Jack Groppo, Robert Hodgen, Steve Summers, John Wiseman, Allen Howard, Lamont Bond, Mark Dunavent and Tate VanHoose.

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ABSTRACT

This report describes a first phase of a project to design, construct and commission an integrated coal/biomass-to-liquids facility at a capacity of 1 bbl. /day at the University of Kentucky Center for Applied Energy Research (UK-CAER) – specifically for construction of the building and upstream process units for feed handling, gasification, and gas cleaning, conditioning and compression. The deliverables from the operation of this pilot plant [when fully equipped with the downstream process units] will be firstly the liquid FT products and finished fuels which are of interest to UK-CAER's academic, government and industrial research partners. The facility will produce research quantities of FT liquids and finished fuels for subsequent Fuel Quality Testing, Performance and Acceptability. Moreover, the facility is expected to be employed for a range of research and investigations related to: Feed Preparation, Characteristics and Quality; Coal and Biomass Gasification; Gas Clean-up/ Conditioning; Gas Conversion by FT Synthesis; Product Work-up and Refining; Systems Analysis and Integration; and Scale-up and Demonstration. Environmental Considerations - particularly how to manage and reduce carbon dioxide emissions from CBTL facilities and from use of the fuels - will be a primary research objectives. Such a facility has required significant lead time for environmental review, architectural/building construction, and EPC services. UK, with DOE support, has advanced the facility in several important ways. These include: a formal EA/FONSI, and permits and approvals; construction of a building; selection of a range of technologies and vendors; and completion of the upstream process units. The results of this project are the FEED and detailed engineering studies, the alternate configurations and the as-built plant - its equipment and capabilities for future research and demonstration and its adaptability for re-purposing to meet other needs. These are described in some detail in this report, along with lessons learned.

EXECUTIVE SUMMARY

PROJECT OBJECTIVE

The overarching objective of this project was to advance the first phase of the design, construction and commissioning of an integrated coal/biomass-to-liquids (CBTL) facility at a capacity of 1 bbl./day at the University of Kentucky (UK-CAER) – specifically for construction of the building and upstream process units for feed handling, gasification, and gas cleaning, conditioning and compression. The main results of the project are the FEED studies, the selection of a range of technologies and technology vendors, the alternate plant configurations and the as-built plant that was deployed - its equipment and capabilities for future research and demonstration and its adaptability for re-purposing to meet other needs.

Outside of these tangible results and deliverables of equipment, CAER conducted serious techno-economic analysis of conceptual 10,000 bbl. /day plants operating in Kentucky and using Appalachian and Illinois Basin coal [(1)]; laid out a Vision for the Facility [APPENDIX 1]; produced a detailed Facility Capabilities and Research Plan, including the rationale and 'fit' with DOE's research objectives and the range of investigations that can be undertaken with such a facility [APPENDIX 2]; and we learned a lot of lessons along the way [APPENDIX 3].

THE REFINERY BUILDING

The building is a 5860 sf. pre-engineered steel frame building, with 40 ft. tall process high bay and 15 ft. low bay office/lab/control room space. The dimensions of the spaces are as follows; High bay: 74'8" X 60' = 4480 sf.; Lab space: 13'11" X 13'9" = 191 sf,; Control room: 13'11" X 24' = 334 sf.; Office: 13'11" X 8'11" = 124 sf.; Utilities and additional rooms = 430 sf. The plant complex includes ancillary systems for power generation, utilities, effluent treatment, ash disposal, and operations, safety control and monitoring systems. Mechanical systems include nitrogen, hydrogen, oxygen, carbon dioxide, natural gas, domestic water, sanitary piping, and general use compressed air piping.

INSTALLED UPSTREAM PROCESS UNITS

A. Feed Processing and Gasification

UK-CAER, with DOE concurrence, made the choice of a foreign-sourced gasifier from China, designed and fabricated by the China Ministry of Education's Key Laboratory of Coal Gasification, East China University of Science and Technology. Substantial savings were achieved in the foreign-sourcing of a greatly less expensive and proven gasifier than that which could be sourced domestically, including all the associated coal handling and preparation equipment. The system includes: 1.) Coal water slurry preparation system (mill, CWS tank, additive container); 2.) Raw material supply system (CWS pump, dewar tank, flow meters, oil tank and pump); 3.) Gas purge and protection system; 4.) Gasification section (stainless gasifier, refractory brick, slag container, burner); 5.) Flame monitoring system; 6.) Gas composition and temperature analysis system; and 7.) Emergency control and shutdown system. ECUST's OMB gasification technology involves using four symmetrically opposite burners to introduce the coal/water slurry to the gasifier in order to produce syngas. The system can produce enough slurry for the gasifier to consume 1 ton of dry coal per day during standard operation which produces approximately 179 lbs/hr of high quality syngas. Under normal operation, the H/CO molar ratio produced in the syngas will be ~0.75/1.

B. Gas Cleaning, Conditioning and Compression

The CBTL facility at UK-CAER is equipped with a secondary purification unit, using aqueous amine solvents, that removes acid gas (CO_2 and sulfur) and acts as a final clean-up of the syngas before it is sent downstream for use in a variety of potential processes. In this section, syngas from the gasification systems primary purification section is compressed to 450 psi and then sent through the acid-gas treatment process, which consists of a traditional aqueous amine solvent based system, using an absorber and stripper. The system itself is also equipped with a hydrolysis reactor to convert COS to H_2S and CO_2, as well as activated carbon beds to remove sulfur down to less than 1ppm.

ENABLING CAPABILITY FOR FUTURE RESEARCH

The deliverables from the operation of this pilot plant [when fully equipped with the downstream process units] will be firstly the liquid FT products and finished fuels which are of interest to UK-CAER's academic, government and industrial research partners. The facility will produce research quantities of FT liquids and finished fuels for subsequent Fuel Quality Testing, Performance and Acceptability. Moreover, the facility is expected to be employed for a range of research and investigations related to: Feed Preparation, Characteristics and Quality; Coal and Biomass Gasification; Gas Clean-up/ Conditioning; Gas Conversion by FT Synthesis; Product Work-up and Refining; Systems Analysis and Integration; and Scale-up and Demonstration. Environmental Considerations - particularly how to manage and reduce carbon dioxide emissions from CBTL facilities and from use of the fuels - will be a primary research objectives.

On an on-going basis, the know-how, show-how associated with the facility is expected to be a key benefit, which can be used as test beds for new technologies and concepts at a level of expenditure that is affordable. It will provide open-access facilities and information in the public domain to aid the wider scientific and industrial community, and a means to independently review vendor claims and validate fuel performance and quality. The facility will be used to build up human capital – the future generation of skilled energy technologists, engineers and operating personnel that will be needed to sustain a CBTL industry. One of the best ways of creating this skills base is to stimulate and fund RD+D at appropriate institutions which have the facilities to teach and train students in the practical application of science and engineering.

Importantly, the facility was purposely designed as modular, skid-mounted, anticipating frequent change-outs; "plug and play"; and future re-purposing. The gasifier was designed to provide twice the flows needed for the FT refinery section to accommodate other slipstream studies; that being at a capacity of 2 bbl. /day gas output [1 ton coal-biomass feed/day; 179 lb./hr. total flow; 65 lb./hr. CO; 3.49 lb./hr. H2]. For research purposes the gasification process can be run in a range of 40-120% of the rated capacity which provides the ability to ramp up/down and provide potential slipstreams for multiple downstream units. The facility will prove to be an important syngas production facility for a variety of future and complimentary research.

REPORT DETAIL

BACKGROUND AND INTRODUCTION

There are significant opportunities for the expanded use of coal for transportation fuels and chemicals by using coal/biomass-to-liquids (CBTL) technology. The use of coal for this purpose can provide additional independence, safeguard the nation's security, allow for the development of new industries, and provide new incentives for coal mining. Moreover, coal-derived fuels are environmentally superior for the production of ultra-clean diesel and jet fuel of interest to the military and the aviation, heavy equipment and trucking industries. Illinois Basin coals are suitable feed stocks for these purposes.

Recognizing these facts, the Congress, per Section 417 of the Energy Policy Act of 2005 directed the Department of Energy to evaluate the commercial and technical viability of advanced technologies for coal-derived transportation fuels. The Congress further directed DOE to enter into agreements with SIU's Coal Research Center, UK's Center for Applied Energy Research, and Purdue's Energy Center to carry out the purposes of the Act. The universities subsequently entered into a Memorandum of Understanding to create the "Coal Fuel Alliance" (CFA) for purposes of sponsoring complementary and joint development and demonstration of technologies for converting Illinois Basin coals to fuels [(1).]

The prospect of CBTL is alluring, however, the deployment of pioneering energy technologies bring with them certain financial, construction, operating and technical risk not associated with proven technologies. Risk can be reduced and deployment stimulated by a variety of means, including price supports, product take-off agreements, tax breaks, and financing incentives for early adopters. It can also be reduced by making so-called "learning investments" for RD+D to reduce the technical hurdles of new energy technologies.

It is for this latter purpose that Purdue University, Southern Illinois University and the University of Kentucky have formed the CFA – to provide a base of "enabling research" and development (RD), and to support demonstrations and deployment (+D) of the technology at commercially-meaningful scale. It is an accepted premise that with successive deployments of a pioneering technology there comes with it learning and improved operational experience. Described as the learning curve, learning-by-doing (for producers) and learning-by-using (for product users), the assumption is that experience leads to reductions in cost or improvements in operating efficiencies. There are a number of technical issues which, if addressed in creative ways, can alleviate some of the risks associated with the adoption of CTL technology.

PROJECT OBJECTIVE

The overarching objective of this project was to advance the first phase of the design, construction and commissioning of an integrated coal/biomass-to-liquids (CBTL) facility at a capacity of 1 bbl./day at the University of Kentucky (UK-CAER) – specifically for construction of the building and upstream process units for feed handling, gasification, and gas cleaning, conditioning and compression. Such a facility was identified in a 'roadmap' [(2)] prepared for DOE by the Coal Fuel Alliance [a consortium of UK, Purdue, and Southern Illinois University] in response to Section 417 of the Energy Policy Act of 2005, which authorized the U.S. Department of Energy to carry out a program to evaluate the commercial and technical viability of advanced technologies for the production of Fischer-Tropsch transportation fuels manufactured from Illinois basin coal.

The facility was and is considered to be the "workhorse" of the Alliance. The deliverables from the operation of this pilot plant [when fully equipped with the downstream process units] will be firstly the liquid FT products and finished fuels which are of interest to UK-CAER's academic, government and industrial research partners. The facility will produce research quantities of FT liquids and finished fuels for subsequent Fuel Quality Testing, Performance and Acceptability; for example, in Purdue's extensive engine test stands sponsored by Rolls Royce, Caterpillar and Cummins Engines. Moreover, the facility was and is expected to be used for a range of investigations related to: Feed Preparation, Characteristics and Quality; Coal and Biomass Gasification; Gas Clean-up/Conditioning; Gas Conversion by FT Synthesis; Product Work-up and Refining; Systems Analysis and Integration; and Scale-up and Demonstration. Environmental considerations - particularly how to manage and reduce carbon dioxide emissions from CBTL facilities and from use of the fuels - will be a primary research objective.

On an on-going basis, the know-how, show-how associated with the facility is expected to be a key benefit, which can be used as test beds for new technologies and concepts at a level of expenditure that is affordable. It will provide open-access facilities and information in the public domain to aid the wider scientific and industrial community, and a means to independently review vendor claims and validate fuel performance and quality. The facility will be used to build up human capital – the future generation of skilled energy technologists, engineers and operating personnel that will be needed to sustain a CBTL industry. One of the best ways of creating this skills base is to stimulate and fund RD+D at appropriate institutions which have the facilities to teach and train students in the practical application of science and engineering.

And, importantly, the facility was purposely designed as modular, skid-mounted, anticipating frequent change-outs; "plug and play"; and future re-purposing. The gasifier was designed to provide twice the flows needed for the FT refinery section to accommodate other slipstream studies; that being at a capacity of 2 bbl. /day gas output [1 ton coal-biomass feed/day; 179 lb./hr. total flow; 65 lb./hr. CO; 3.49 lb./hr. H2]. For research purposes the gasification process can be run in a range of 40-120% of the rated capacity which provides the ability to ramp up/down and provide potential slipstreams for multiple downstream units. The facility will prove to be an important syngas production facility for a variety of future and complimentary research.

PRINCIPAL TASKS

- Task 1.1 Technology Selection.
- Task 1.2 FEED Study.
- Task 1.3 A&E Plans and Specifications for Refinery Building.
- Task 1.4 Construction of Refinery Building.

- Task 2.1 Cost Estimation & Feasibility Study for Incorporation of Feed Handling and Preparation, Gasifier and Gas Cleaning/Conditioning and Compression Sections.

- Task 3.1 Detailed Design, Fabricate and Install an ECUST Opposed Multi-Burner (OMB) Coal Gasifier
- Task 3.2 Detailed Design of Syngas Work-up and Conditioning and Compression Section.
- Task 3.3 Fabricate and Install Syngas Work-up and Conditioning and Compression Section.
- Task 3.4 Shakedown and Commissioning of Opposed Multi-Burner (OMB) Coal Gasifier Section and Syngas Work-up and Conditioning and Compression Section.

RESULTS AND DELIVERABLES

A. <u>Main Accomplishments</u>

Since 2007, UK with support of DOE has pursued the tangible construction and development of a coal/biomass-to-liquids facility at a capacity of 1 bbl./day. Since that time we have advanced the facility in several important ways. These include: a formal EA/FONSI, and permits and approvals; construction of a building to house the refinery; selection of a range of technologies and vendors; and the design, fabrication and installation of upstream process units for feed handling, gas cleaning, conditioning and compression, and gasification.

First and foremost, the main results of this project are the FEED studies, the selection of a range of technologies and technology vendors, the alternate plant configurations and the ultimate plant planned to be built and deployed - its equipment and capabilities for future research and demonstration and its adaptability for re-purposing to meet other needs.

A run-down of the tasks and our accomplishments follows.

Task 1.1. With respect to technologies and technology vendors, CAER evaluated a variety of technologies and alternate configurations for the principal processing units, from Natural Gas Reforming (Unitel); coal-biomass gasification (Conoco-Phillips, KBR, GE-Texaco, Sasol-Lurgi, Shell, SilvaGas™, ECUST); to water-gas-shift [Chart, ZETON]; to Fisher-Tropsch (F-T) Synthesis (Rentech, Velocys and Chart); to Fluid Catalytic Cracking (W.R. Grace); to Hydrocracking, Dehydrogenation and Alkylation (UOP).

Task 1.2. Key technical information for each unit process was provided to CAER's engineering contractor, ZETON, for use in completing a FEED Study. The purpose of the FEED Study was to firm up the process design and develop the Process & Instrumentation Diagrams (P&IDs). Zeton, Inc. investigated the optimal skid layout to accommodate the equipment and process units, and suggested an appropriate control system based on its experience. Finally, Zeton provided a +/-10% cost estimate and a more precise schedule for the detailed design, procurement and construction phase of the project.

Task 1.3 and 1.4. Meanwhile, CAER engaged the Architectural & Engineering (A&E) company, Murphy Graves Architects, assisted by CMTA Engineering, to provide design/build services related to the general site work, building shell, materials of construction, thermal and moisture control, heating, air conditioning and ventilation, fire protection, finishes, equipment, furnishings, special construction, conveying systems, lighting, mechanical, electrical, plumbing, and energy efficiency, and special building utility services. Following receipt of the A&E Plans and Specs, the project was bid with the winning bidder being Parco Construction Company. Ground was broken in November 2011, and a Certificate of Substantial Completion and Beneficial Occupancy was issued July 2012 for the facility.

Task 2.1. In addition, CAER conducted a Cost Estimation & Feasibility Study for incorporation of feed handling and preparation, gasification and gas cleaning/conditioning and compression sections. The study confirmed the requirements for potentially incorporating an experimental gasifier and the necessary feed handling and preparation, and gas cleaning/conditioning and compressions sections.

Task 3.1, 3.2. Following on from our Cost Estimation & Feasibility Study, CAER pursued the design, installation and commissioning of an ECUST opposed multi- burner (OMB) entrained-flow coal gasifier capable of generating synthesis gas sufficient for production of 1 bbl/day liquids. The coal-biomass feed system, gasifier and ancillary equipment were subsequently fabricated in China and delivered in December 2013. Installation of the gasifier and balance of plant [BOP] was complete in early 2015. The main equipment provided for the system includes: (1) Coal water slurry preparation system (mill, CWS tank, additive container); (2) Raw material supply system (CWS pump, dewar tank and flow meters); (3) Gas purge and protection system; (4) Gasification section (stainless gasifier, refractory brick, slag container, burner); (5) Cyclones for particulate separation and a water washing system (6) Full control system including gas analysis.

Task 3.3. Finally, CAER engaged the firm of China Electronics and Engineering Design Institute (CEEDI) to perform a detailed design of syngas work-up and conditioning and compression section compatible with the OMB gasifier. The design/fabrication of the skid-mounted units, was complete at the end of 2014. Installation of the equipment was completed during the summer of 2015.

Task 3.4. After installation of the gasifier and acid-gas clean-up plant, CAER performed shakedown and commissioning to verify compatibility and performance of the upstream refinery units.

B. Other Outcomes

Also since the beginning of this project in 2007, and in part or in direct response to DOE's Peer Review Process, we've also reported about some serious techno-economic analysis we conducted for conceptual 10,000 bbl. /day plants operating in Kentucky using Appalachian and Illinois Basin coals (1). We've laid out a Vision and Objective for the facility [APPENDIX 1]; that being:

> The overarching objective of this project is to advance the design, construction and commissioning of an integrated coal/biomass-to-liquids (CBTL) facility at a capacity of 1 bbl. /day at the University of Kentucky (UK-CAER). The university intends to concentrate resources, create a critical mass of expertise, and provide a focal point for RD+D on fuels and chemicals derived from coal and biomass.
>
> On an on-going basis, the know-how, show-how associated with the facility is expected to be a key benefit, which can be used as test beds for new technologies and concepts at a level of expenditure that is affordable. It will provide open-access facilities and information in the public domain to aid the wider scientific and industrial community, and a means to independently review vendor claims and validate fuel performance and quality. The facility will be used to build up human capital – the future generation of skilled energy technologists, engineers and operating personnel that will be needed to sustain a CBTL industry.

We've produced a Facility Capabilities and Research Plan [APPENDIX 2], including the rationale and 'fit' with DOE's research objectives:

> . . . The project and facility directly supports DOE/NETL's mission of "ensuring the availability of near-zero atmospheric emission, abundant and affordable, domestic energy to fuel economic prosperity, strengthen energy security, and enhance environmental quality". In addition, this facility complements NETL's key focus areas of technologies that will enable 1.) The full realization of the clean-energy potential of the nation's abundant domestic coal supplies, while meeting environmental and climate change goals; and 2.) Moving to a hydrogen economy, including hydrogen from coal gasification. The nation's military also have a keen interest in securing alternative battlefield and jet fuels derived from coal and biomass, as do the nation's aviation, heavy equipment and trucking industries. Finally, the project advances DOE's objective of labor force development, and of international Science and Technology exchange – in this instance our significant collaboration with China, and particularly that nation's Key Laboratory of Coal Gasification, East China University of Science and Technology.

We've described in good level of details the range of investigations that can be undertaken with such a facility related to each of the topics below [APPENDIX 2]:

> - Feed Preparation, Characteristics and Quality
> - Gas Clean-up/Conditioning
> - Product Work-up and Refining
> - Systems Analysis and Integration
> - Coal and Biomass Gasification
> - Gas Conversion by FT Synthesis
> - Fuel Quality Testing, Performance and Acceptability
> - Environmental Considerations – particularly the means to manage/reduce CO_2
>
> The deliverables from the operation of this pilot plant will be first the liquid FT products and finished fuels, which are of interest to UK-CAER's academic, government and industrial research partners. Furthermore, it will be a test platform to take lab scale work to the next level of scale-up and to have a fully integrated gas to final products continuous proof-of-concept facility. Constituting a true process development unit, it will enable different catalyst formulations, gas compositions,

temperatures and pressures as well as recycle optimizations to be done. The facility would carry out research on synthesis gas (syngas) derived from coal and biomass gasification. Important areas of investigation will include gas cleaning and conditioning to assure the necessary syngas quality for FT synthesis. Research would include experiments on water-gas-shift and Fischer-Tropsch processes as well as on catalyst structure-function properties with the ultimate goal of reducing the costs of the process and helping produce a more environment-friendly liquid fuel. Through successful research, the proposed project would help manage and reduce carbon dioxide emissions from CBTL facilities and from use of the fuels and would help to develop facilities and personnel to sustain a domestic coal/biomass-to-chemicals industry.

And, we've learned a lot of lessons along the way [APPENDIX 3]. DOE's guidance and concurrence has been sought at every important decision point, particularly at the point of placing firm orders for construction and major equipment. DOE's guidance has been invaluable in assuring that we take the 'long view' of this project and facility. A prime example was the decision to abandon auto thermal reforming of natural gas in favor of coal-biomass gasification as a means of producing syngas for the facility. This was a right and appropriate decision as it greatly increased the long-term efficacy of the facility: auto thermal reforming of natural gas is a well-established and proven technology whereas coal gasification and the related deep gas clean-up processes represented fruitful fields of future investigation. Our facility can be used for research and investigations related to both the upstream and downstream process units.

OVERALL PROCESS SCHEME FOR FACILITY WHEN COMPLETED

A. Main Process Units

The main process units of the UK's eventual CBTL facility will consist of feed preparation [coal and coal/biomass water slurry], gasification, gas cleaning and conditioning, gas conversion by FT synthesis and product work-up and upgrading. **This grant [no. DE-FC26-08-NT05988] made possible the construction of the refinery building, and fabrication of the upstream processing units for coal/biomass water slurry feed preparation, gasification and gas cleaning, and ancillary systems for power generation, utilities, effluent treatment, ash disposal and automated controls.** A second grant now in process [DEFC2612FE0010482] will provide for fabrication, installation and commissioning of the downstream refinery units for FT synthesis and product work–up and upgrading. Once the facility is completed, the main process units are illustrated in the simplified process flow diagram provided as Figure 1, and will eventually include:

- Coal/biomass water slurry feed preparation;
- A coal/biomass gasifier for syngas production;
- Water-gas shift reactor for adjustment of H:CO ratio;
- An aqueous amine-based stripper/scrubber and carbon bed system for gas cleaning and conditioning;
- A micro-channel reactor for FT synthesis; and
- A hydrocracker to crack the heavier fractions and optimize diesel yields.

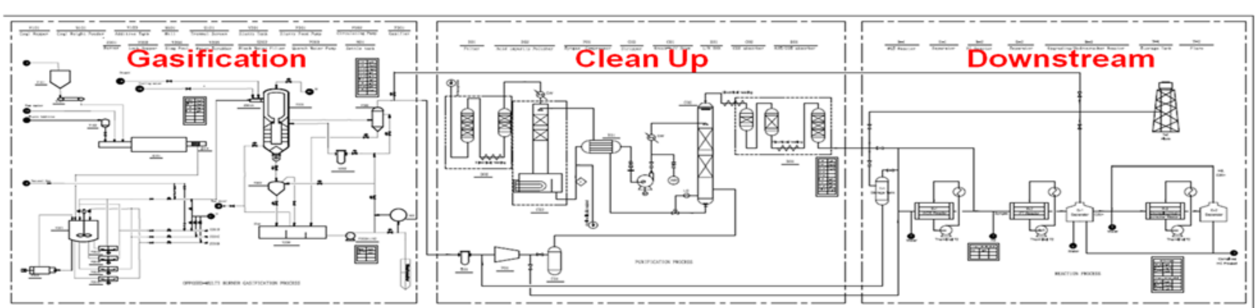

Figure 1: Process Flow Sheet for Facility

B. Capacities and Stream Flows

Operation of the FT PDU Facility would have the capability to produce approximately 1 barrel per day of mixed hydrocarbon fuels and feed stocks ranging from diesel, gasoline, naphtha, waxes, and light gases, depending on the upgrading processes employed downstream. Streams flows are shown in

Figure 2.

This report provides detailed descriptions of the facilities that were made possible thru this grant [no. DE-FC26-08-NT05988], including the refinery building that was constructed, and the two upstream process sections for gasification [including feed prep] and acid gas cleanup.

THE REFINERY BUILDING

Laboratory facilities are complex, technically sophisticated, and mechanically intensive structures that are expensive to build and to maintain. The design and construction of such facilities come with certain risks that must be managed – ranging from quality and safety, cost management, time management, scope and change management, procurement and contracts, people management, information management, and external influences such as regulatory compliance and community relations. Research scale pilot plants pose particular challenges with respect to critical flows and requirements that need specialized, scale-specific knowledge and expertise to simplify the design and lower the capital cost.

Hundreds of decisions must be made before and during new construction - decisions that will determine how successfully the facility will function when completed and how successfully it can be maintained once put into service. These decisions will also determine whether the project comes in "on time" and "on budget". Among the decisions are considerations about the site work, building shell, materials of construction, thermal and moisture control, heating, air conditioning and ventilation, fire protection, finishes, equipment, furnishings, special construction, conveying systems, lighting, mechanical, electrical, plumbing, and energy efficiency, and special building utility services. These considerations extend to, besides the main refinery sections, other parts of the plant, including feed preparation and conveyance, gas cleaning, solid and effluent treatment/disposal, Environmental Assessments and permitting, evaluations of hazards and operability [HAZOP], and logistics regarding feed and products storage and transportation.

A. Dimensions and Floor Plan – High bay, Laboratory, Control Room, Office

A 5860 sf. pre-engineered steel frame building, with 40 ft. tall process high bay and 15 ft. low bay office/lab/control room space.
High bay: 74'8" X 60' = 4480 sf.;
Lab space: 13'11" X 13'9" = 191 sf.;
Control room: 13'11" X 24' = 334 sf.;
Office: 13'11" X 8'11" = 124 sf.;
Utilities and additional rooms = 430 sf.
See Figure 3 for Floor Plan. Figure 4 shows A&E drawings of the building exterior and interior high bay space.

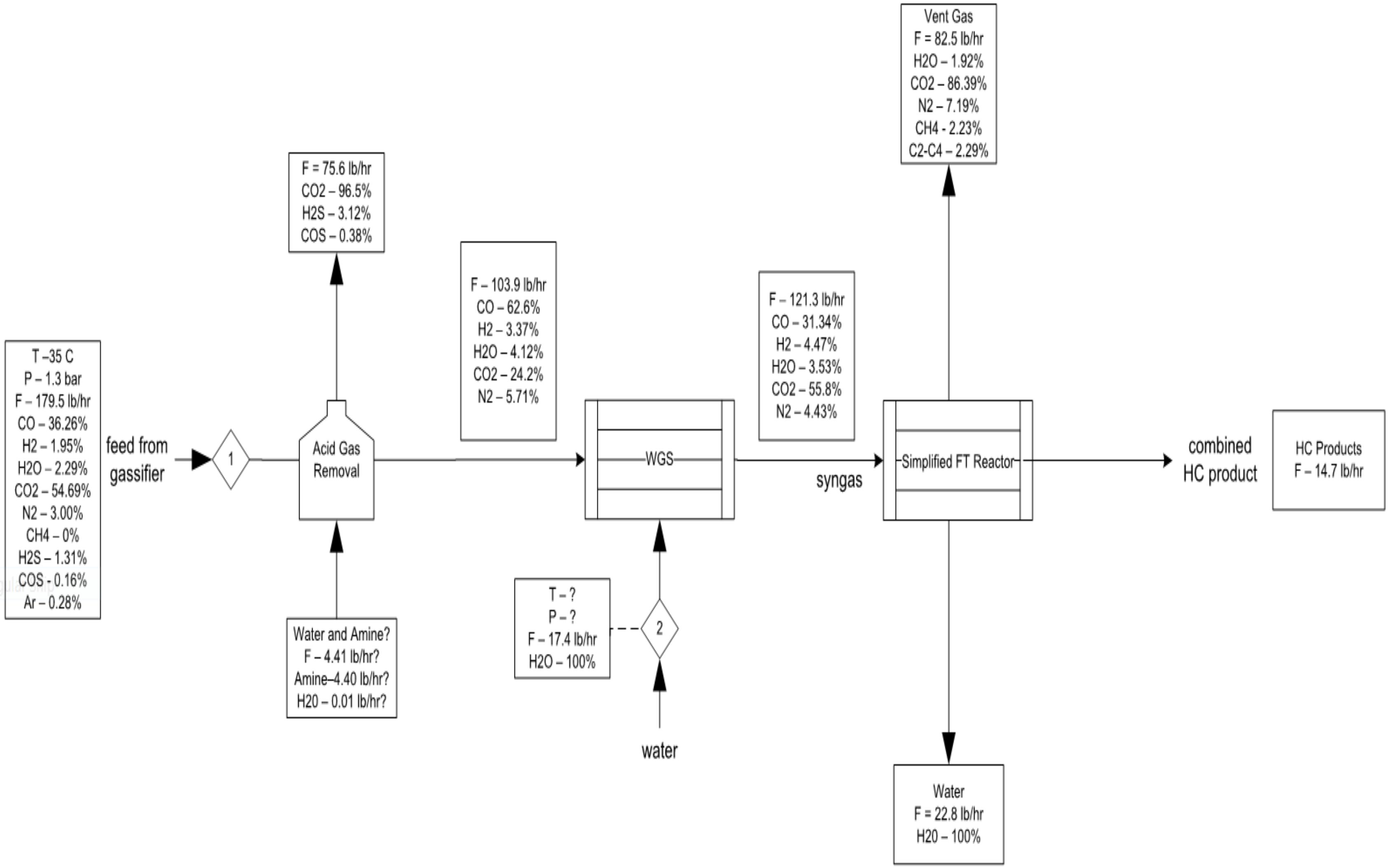

Figure 2: Process Flow Sheet – Unit Processes and Output

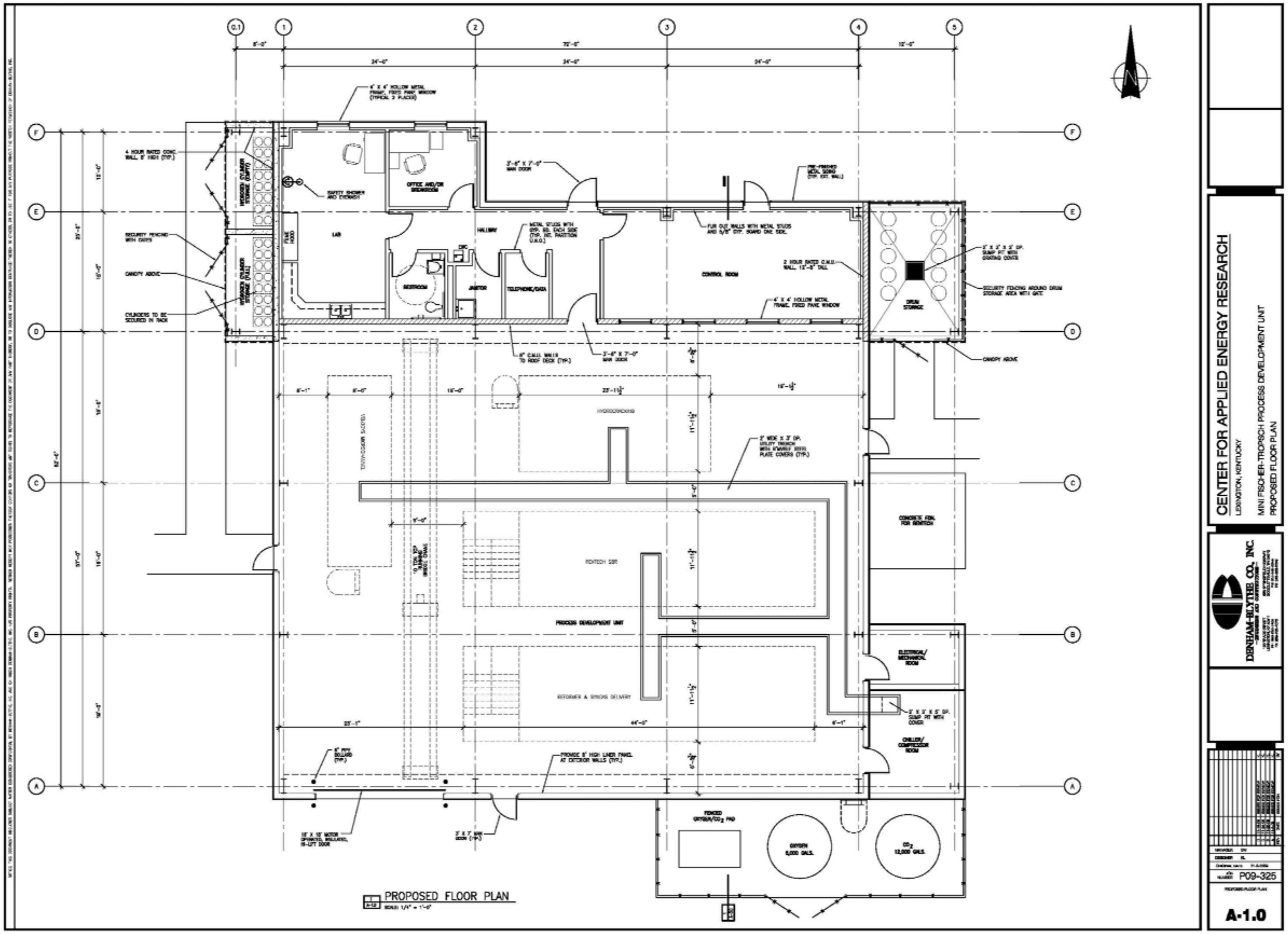

Figure 3: A&E Drawing - Building Floor Plan

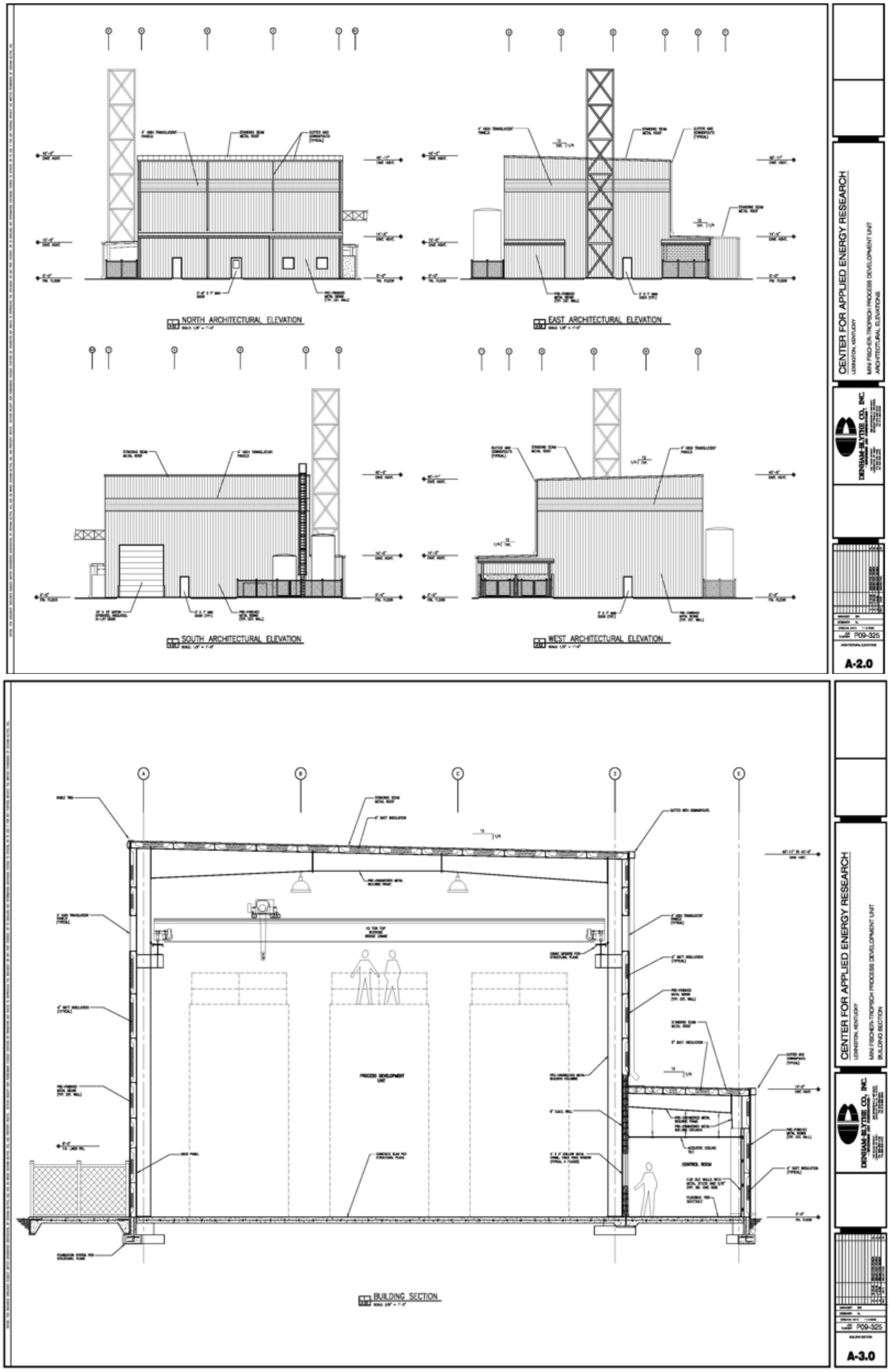

Figure 4: A&E Drawings - Building Exterior and Interior High bay Space

B. Auxiliaries and Building Services

The plant complex includes ancillary systems for power generation, utilities, effluent treatment, ash disposal, and operations, safety control and monitoring systems. Mechanical systems include nitrogen, hydrogen, oxygen, carbon dioxide, natural gas, domestic water, sanitary piping, and general use compressed air piping. Piping also includes collection piping for flare gas. Other systems include the HVAC, full exhaust and make-up air for the 6' fume hood [including polypropylene acid waste piping to dilution pit from hood sink prior to connection to sanitary sewer]; mechanical exhaust systems to Simplex Fire Alarm Control Panel (FACP) to monitor for smoke; electrical service to building and distribution of power to process skids; power provisions for HVAC and ventilation components; Fire Alarm and Communications tie-in; full security system including audio-visual devices, intrusion and proximity card installation for access.

The facility is supported by common-use facilities of CAER, including coal storage and drying, crushing room, dedicated and secured barrel storage area for good product, and solid and hazardous waste storage [with appropriate similar spill prevention measures such as containment walls, concrete pads, diked areas, and spill pallets].

C. Finished Building Exterior and Interior

Figure 5: Photo - Exterior of Finished Building

Figure 6: Photo - High bay Space, 15-ton Crane, Roll-up Door for Equipment Moving

Figure 7: Photo - Materials Prep and Analysis Laboratory

Figure 8: Photo - Control Room

Figure 9: Photo - View of High bay from Control Room

FEED PREPARATION AND GASIFIER SECTIONS

A. Principal Reactions and Duty of Gasifier

Gasification of coal, or other carbonaceous material has been used for generation of combustible gases since the late 1700s. The principle reactions which take place during the gasification of pure carbon are those involving carbon, oxygen, and hydrogen and in particular their compounds carbon monoxide, carbon dioxide, water (or steam), and methane. Important reactions identified in the gasification of coal are given in reactions [1] to [14] below. Reactions [1] to [5] are involved in the actual gasification of the coal while reactions [6] to [14] are responsible for governing the gas composition.

Devolatilization

Coal → Char + Volatiles [1]

Heterogeneous Gasification

$C + 1/2\ O_2 \rightarrow CO$ [2]

$C + CO_2 \rightarrow 2\ CO$ [3]

$C + H_2O \rightarrow H_2 + CO$ [4]

$C + 2\ H_2 \rightarrow CH_4$ [5]

Homogeneous Combustion

$CO + 1/2O_2 \rightarrow CO_2$ [6]

$H2 + 1/2\ O_2 \rightarrow H_2O$ [7]

$CH4 + 2\ O_2 \rightarrow CO_2 + 2H_2O$ [8]

$H_2S + 3/2\ O_2 \rightarrow SO_2 + H_2O$ [9]

$COS + 3/2\ O_2 \rightarrow CO_2 + SO_2$ [10]

Homogeneous Equilibrium

$H_2O + CO \leftrightarrow H_2 + CO_2$ [11]

$CO + 3H_2 \leftrightarrow CH_4 + H_2O$ [12]

$SO_2 + 3H_2 \leftrightarrow 2\ H_2O + H_2S$ [13]

$COS + H_2O \leftrightarrow CO_2 + H_2S$ [14]

In gasification processes the reactions involving free oxygen can be considered to go to completion and usually the carbon conversion is 95% or higher. Due to the high operating temperatures of most processes, the reactions reach close to equilibrium and the final gas composition is controlled by the CO shift reaction [11] and the steam methane reforming reaction [12]. In the initial pyrolysis phase [1], volatiles are driven off from the coal. After which, the vapor phase reactions proceed quickly. The heterogeneous char gasification reactions [2-5] are the determining factor in the overall reaction kinetics. Typically, the temperatures of gasification reactors are sufficiently high that methane is usually the only hydrocarbon present in any measureable quantity.

The operating pressure and temperature of the gasifier also have an influence on the gas composition. The contents of CH_4 and CO_2 in the synthesis gas cause pressure increases. Conversely, as the gasification temperature increases, the methane content drops and the H_2/CO ratio shifts toward increasing CO. Typical industrial gasification processes today operate in the range 25−80 bar depending on application. At these pressures, temperatures of above 1250 °C are required in order to produce a synthesis gas with a low (<0.5 mole %) methane content. At lower pressures (<2 bar) and similar temperatures, such as that used in the UKY-CAER/ECUST pilot plant, the syngas conversion rate will be lower [3]. While operating at higher pressures is ideal, due to the nature of the research pilot facility as well as the flexibility and safety requirements of the facility, lower operating pressures were designed for the CAER's pilot plant.

B. The Selection of ECUST's Opposed Multi-burner Gasifer

Coal gasification is a key technology among clean coal technologies to convert coal to energy or other chemical products in an environmentally acceptable and efficient way. Gasifiers can be classified as slagging or non-slagging, depending on the temperature of operation. If the operating temperature is above the melting point of the ash in the coal, it is called slagging. The high temperatures lead to the destruction of volatile heavier components from the coal, leading to a synthesis gas with predominantly hydrogen and carbon monoxide. Slagging, entrained gasifiers usually use fine coal in either a slurry with water or as pulverized feed. The non-slagging gasifiers fall into two categories: the "moving bed" or "fluidized bed units." Due to the lower temperatures, some of the devolatilized products from the coal are carried out of the gasifier with the syngas, which are later separated, used or recycled. Moving bed gasifiers typically require a feed coal of at least ¼" size, whereas fluidized bed gasifiers use pulverized coal feed and air or oxygen and steam to fluidize the fine coal.

Within the gasification field, entrained flow gasification [slagging gasifiers] is a leading technology because it can be applied to a large variety of coals and used on a large-scale due to the system's ability to operate at elevated temperature and pressure. Entrained flow gasification can use either coal-water slurry (CWS) as a feed stock, such as GE (Texaco) process [(4) (5)] and Global E-Gas process [(6)], or dry coal, such as Shell gasification [(7) (8)], Prenflo gasification [(9) (10)] and GSP gasification [(11)].

A range of gasifiers - Conoco-Phillips, KBR, GE-Texaco, Sasol-Lurgi, Shell and others - were investigated for purposes of this project. Some OEMs declined to design and fabricate at this small capacity of 1 bbl./day needed for research purposes; others tendered estimates upward of $10M+ for the gasifier only. The eventual recommendation from UK's EPC contractor was to procure Future Energy Resources Corporation's [now Rentech's] SilvaGasTM biomass gasification process at a cost estimate of $5.5-5.9 million. At this point, a decision was made to go with a much less expensive and potentially more reliable Chinese-made coal-biomass gasifier for reasons of expense and compatibility with the research-scale needed for this application.

With support of China's national high technology research and development program (the 863 Program), East China University of Science and Technology [ECUST], along with Yankuang Lunan Chemical Fertilizer Plant and China Tianchen Engineering Corporation Co. Ltd (TCC) have developed the coal-water slurry gasification technology with opposed multi-burners (OMB). A general flow schematic of the ECUST-OMB technology is shown in Figure 10, which is based on the principle that impinging flows strengthen the mixing of the particles during the gasification process. Successive field deployments and industrial demonstrations of larger and larger capacity gasifiers using this technology have greatly promoted the development of the coal-to-chemicals industry in China and that nation's energy production using coal in a more environmentally friendly method [(11) (12) (13)]. ECUST's OMB gasification technology has become one of the leading technologies in the world gasification market [(14)].

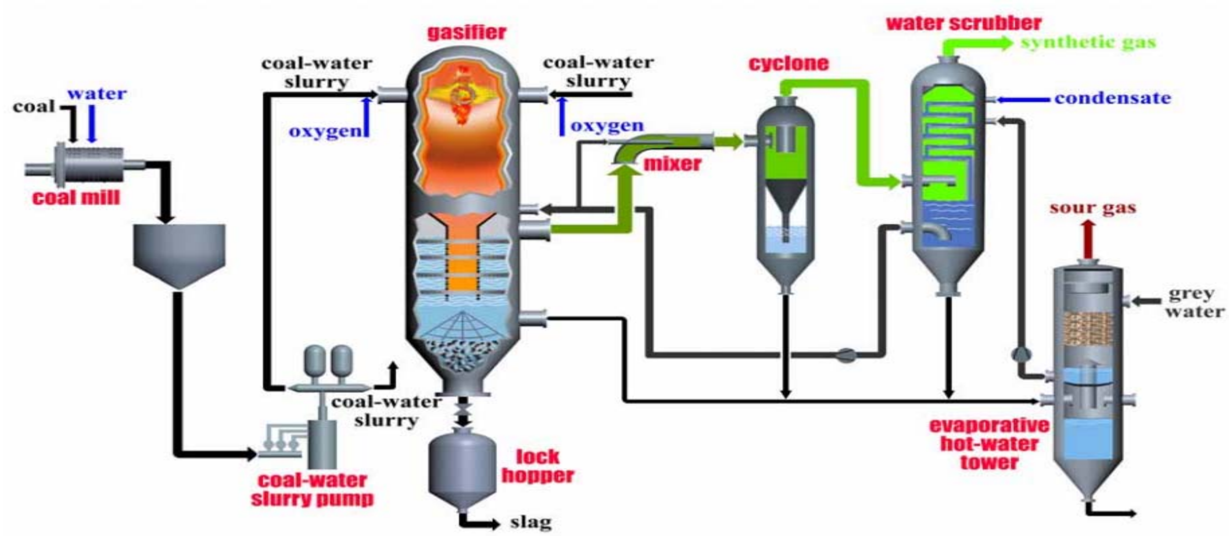

Figure 10: Schematic - ECUST OMB gasification process

C. Description of ECUST's Feed Preparation and OMB Gasifier

Substantial savings were achieved in the foreign-sourcing of a greatly less expensive and proven gasifier than that which could be sourced domestically, including all the associated coal handling and preparation equipment. UK-CAER, with DOE concurrence, made the choice of an ECUST gasifier and system for purposes of this project. The system includes: 1) Coal water slurry preparation system (mill, CWS tank, additive container); 2) Raw material supply system (CWS pump, dewar tank, flow meters, oil tank and pump); 3) Gas purge and protection system; 4) Gasification section (stainless gasifier, refractory brick, slag container, burner); 5) Flame monitoring system; 6) Gas composition and temperature analysis system; and 7) Emergency control and shutdown system. ECUST's OMB gasification technology involves using four symmetrically opposite burners to introduce the coal/water slurry to the gasifier in order to produce syngas. This system can produce enough slurry for the gasifier to consume 1 ton of dry coal per day during standard operation which produces approximately 179 lb./hr. of high quality syngas. Under normal operation, the H_2/CO molar ratio produced in the syngas will be ~0.75/1. The OMB-CWS gasification process at UK-CAER, shown in Figure 11, consists of 4 main sections: feedstock preparation, gasification, raw syngas primary purification, and water treatment section.

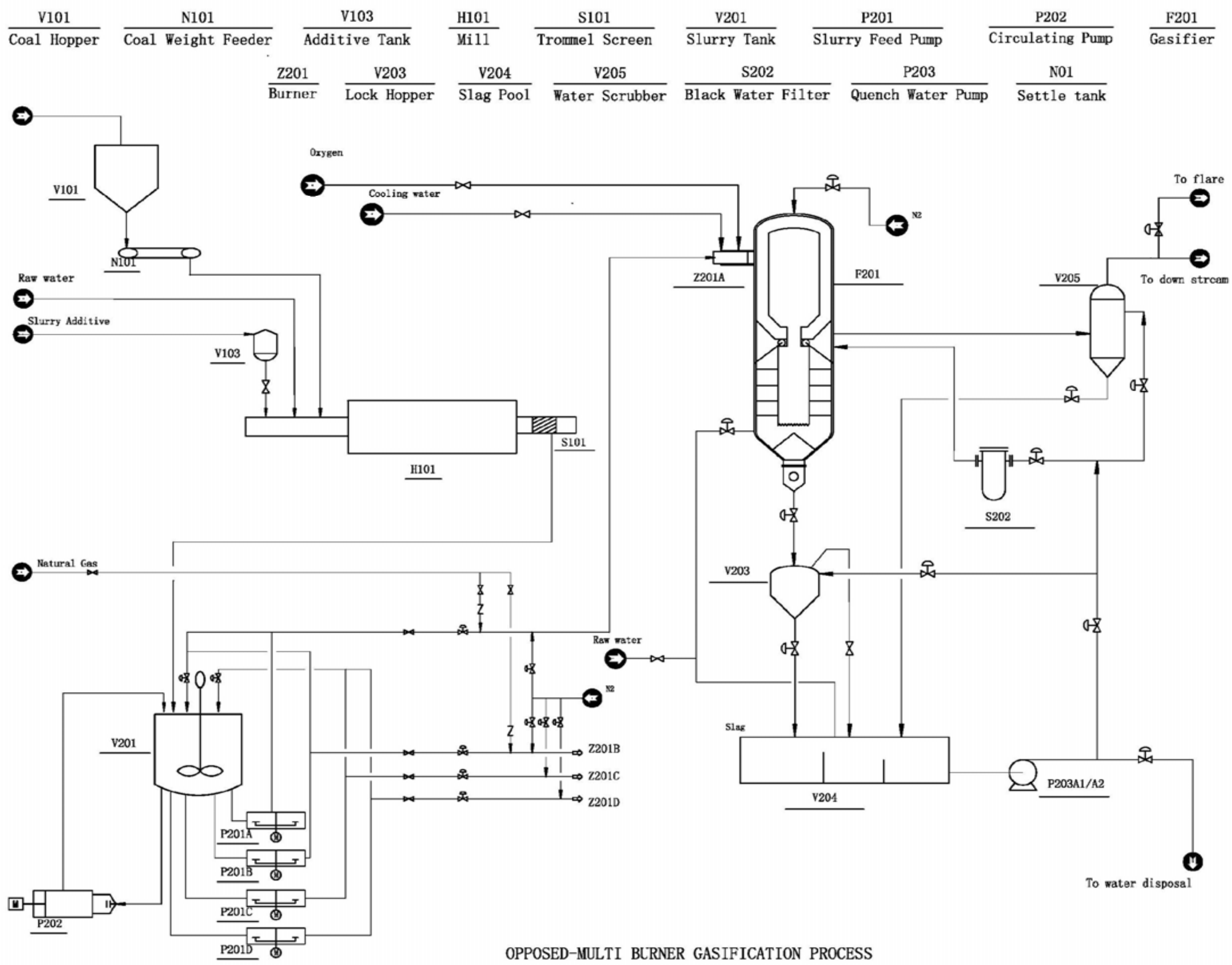

Figure 11: Process Flow Sheet - OMB Gasification Process

Coal/Biomass Feed Preparation: One advantage of this system involves having a full feed preparation system on site, which allows for on-demand slurry preparation and the ability to blend biomass or other feedstocks prior to gasification. This portion of the process consists of a coal hopper, weight feeder, coal mill, slurry tank and mixer. Raw coal or coal/biomass [optimally torriefied wood] mix is first added to the feed preparation unit. In the feed preparation unit, as shown in Figure 12, the coal/biomass is weighed and then introduced to the ball mill where the particle size is reduced while simultaneously being mixed with water of an appropriate amount. After blending, the CWS is stored in a tank and kept suspended with a mixer. Once the slurry is prepared, it is then introduced concurrently with oxygen to the gasifier via four burners that are located exactly opposite one another in order to create significant mixing effects within the gasification chamber.

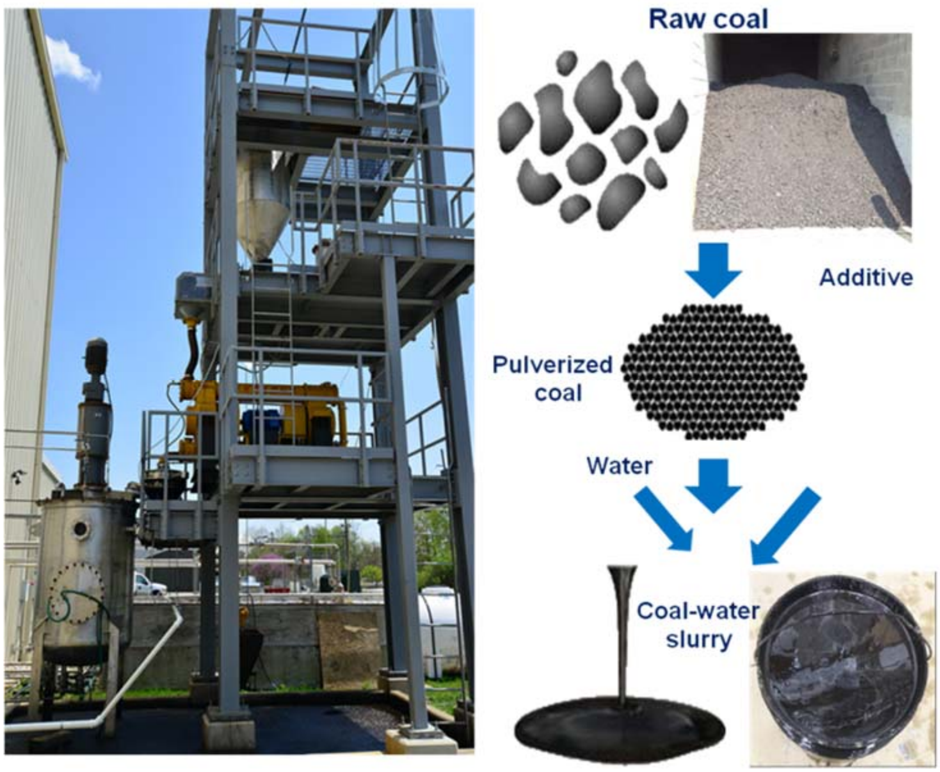

Figure 12: Photo and Illustration - Feed Preparation Unit

Gasifier: The gasifier, as shown in Figure 13, which is 25 ft. tall and 6ft in diameter, consists of two parts; the gasification chamber where the slurry reacts and the quench chamber where the reaction is extinguished. Upon entering the gasification chamber the coal/biomass water slurry and oxygen react to produce crude syngas and molten ash which then pass to the quench chamber through a cross flow water spray and subsequent water bath. This acts as a first wash for the raw syngas and removes large ash particles while quickly removing heat. Moreover, the syngas is completely saturated in this step due to the requirements of downstream purification processes. In the quench chamber, a significant amount of slag water needs to be removed and is sent to the water purification section for treatment. The dirty slag water enters the slag pool that is equipped with a weir system to capture solids while letting the clean water recycle back to the quench chamber. After the washed syngas leaves the quench chamber, it proceeds to the primary purification section. Here the syngas passes through a water scrubber which removes about

80% of the unconverted particles and remaining ash. The water scrubber is the last step in the gasification process before the syngas continues downstream to the acid gas cleanup unit for further processing.

Figure 13: Photo - OMB Gasifier

OMB-CWS technology has many advantages over typical entrained flow gasification systems such as: improved flow distribution, enhanced residence time and carbon conversion, high syngas production with low coal/oxygen consumption, wide capacity range (40-120% of rated capacity) and low process pressure drop along with low operating pressures (30 psi).

One additional significant feature of the gasification system is the DeltaV operating system. The system continuously monitors and records data from instruments such as pressures, temperatures, levels, and flows. It also provides the ability to control every aspect of the system including pumps and valves while concurrently providing safety interlocks and hazardous gas alarms. Included with the control system is an imaging system that provides a live video stream of the flame inside the gasifier which is a unique feature for experimental gasification units of this type. The DeltaV operating system and flame visualization system are shown in Figure 14. While the system currently only has the ability for off-line gas analysis (Gas Chromatograph – SRI 8610C), using multiple sampling ports, an on-line gas analyzer will be installed in the near future.

Figure 14: Photo - DeltaV Operating System and Flame Visualization System for Gasifier

ACID GAS REMOVAL [AGR] SECTION

A. <u>Principal Reactions and Duty of AGR Plant</u>

Using aqueous amine solvents is a common method for the removal of sulfides and CO2 from gas mixtures. For the past decade or more, to improve the economics of the process, the gas cleanup industry has been committed to developing solvent formulations with better performance. The Research Institute of Nanjing Chemical Industrial Group (NCIG) has focused on gas purification based on amine solutions for nearly 50 years, and accumulated vast experience in the area of shift gas desulfurization and decarbonization. The developed NCMA solvent used in this process is a patented technology, which has been optimized using a propriety solvent formulation. The NCMA solvent improves the absorption and regeneration performance of the process, and reduces the energy consumption of regeneration as well as corrosion. After the NCMA purification, the dry desulfurization technology of Hubei Huashuo Technology Co. Ltd. is used for the removal of sulfides in the treated gas to meet the technical requirements of the downstream processes.

The removal of CO_2 and H_2S in the feed gas is achieved by using the NCMA solvent in the purification unit. The reaction of the aqueous solution of NCMA with CO_2 occurs as follows:

$$CO_2 + H_2O \xrightarrow{k_{OH}} H^+ + HCO_3^- \quad [1]$$
$$H^+ + R_3N \rightarrow R_3NH^+ \quad [2]$$
(1) + (2):
$$R_3N + CO_2 + H_2O \rightarrow R_3N^+ \cdot HCO_3^- \quad [3]$$

Reaction (1) is the hydration of CO_2, which controls the overall reaction rate. As the reaction rate constant (kOH) of reaction (1) at 25℃ is 10^4 L/mol*s with [OH] =10^{-3}~10^{-4}mol/L, therefor the overall reaction [3] is very slow.

When a small amount of activator (R'NH) is added into the tertiary amine solution, the absorption of CO_2 proceeds as follows:

$R_2^{'} NH + CO_2 \xrightarrow{k_{AM}} R_2^{'} NCOOH$ [4]
$R_2^{'} NCOOH + H_2O \rightarrow R_2^{'} NH + H^+ + HCO_3^-$ [5]
(4) + (5) + (2):
$R_3N + CO_2 + H_2O \rightarrow R_3NH^+ \cdot HCO_3^-$ [6]

The total reaction rate for the overall reaction [6] is controlled by reaction [4], which is a second order reaction, with the reaction rate constant (kAM) at 25℃ is 10^4 L/mol*s. When the activator (1~4%) is added, the concentration of the free amine ([NH]) is above 10^{-2} mol/L. For the typical activator, the reaction rate of reaction [4] is relatively slow, however due to the ratio of kAM[R2'NH] to kOH[OH] being about 10~100, there is a significant effect on the absorption rate. Therefore, the reaction rate of reaction [4] is much faster than that of reaction [1]. For the active amine in the NCMA solution, which has molecular structure with steric hindrance, the R2'NCOOH is very unstable. Thus, the absorption rate is much faster. In conclusion, the addition of the active amine changes the absorption mechanism of the tertiary amine solution with CO_2. The active amine absorbs CO_2 on the surface, and then passes CO_2 to the liquid phase before the active amine is regenerated.

From a chemistry viewpoint, the reactive group of the tertiary amine is a tertiary nitrogen atom, which will form the bicarbonate ion when reacting with CO_2 and can be regenerated by heating. Therefore, the steam consumption of regeneration is much lower than that of the carbamate formed by reaction of primary and secondary amines with CO_2. After the NCMA purification, the dry desulfurization technology of Hubei Huashuo Technology Co. Ltd. is used for the removal of sulfides in the crude treated gas and acid gas. For the H_2S removal in the treated gas, which is composed of CO and H_2, it is reacted with the DS-1 hypoxia-type fine desulfurizer. The DS-1 consists of a metal oxide main component, and the reaction is below:

$MO + H_2S \rightarrow MS + H_2O$ (M for metal)

For the H_2S in the acid gas, which is composed of mainly CO_2, it will be removed by the cheaper T103 activated carbon desulfurizer. The T103 desulfurizer works under an O_2 atmosphere and the reaction is:

$H_2S + {}^1/_2\, O_2 \rightarrow S + H_2O$

The COS in the crude treated gas and rejected acid gas, is first hydrolyzed to H_2S using a COS hydrolysis catalyst. Then H_2S is removed by the corresponding H_2S desulfurizer, based on the particular steam, discussed above. The catalyst used for the hydrolysis of COS in the crude treated gas and acid gas is T504 and T504A respectively. The latter is specially used for atmospheres with high concentrations of CO_2. The reaction under the two catalysts is the same and occurs as shown:

COS+H_2 O→H_2 S+CO_2

B. Description of AGR Plant

The CBTL facility at UK-CAER is equipped with a secondary purification unit as shown in Figure 15 that removes acid gas (CO_2 and sulfur) and acts as a final clean-up of the syngas before it is sent downstream for use in a variety of potential processes. In this section, syngas from the gasification systems primary purification section is compressed to 450 psi and then sent through the acid-gas treatment process, which consists of a traditional aqueous amine solvent based system, using an absorber and stripper. The system itself is also equipped with a hydrolysis reactor to convert COS to H_2S and CO_2, as well as activated carbon beds to remove sulfur down to less than 1ppm.

Figure 15: Photo - Acid Gas Removal Unit (left) and Activated Carbon Bed (right)

After leaving the gasification section the crude syngas enters the acid gas cleanup section where it proceeds through the system and exits in two streams: rejected acid gas and clean syngas. The rejected acid gas is sent to the flare for disposal while the clean syngas is sent downstream for further processing. The process flow diagram is shown below in Figure 16.

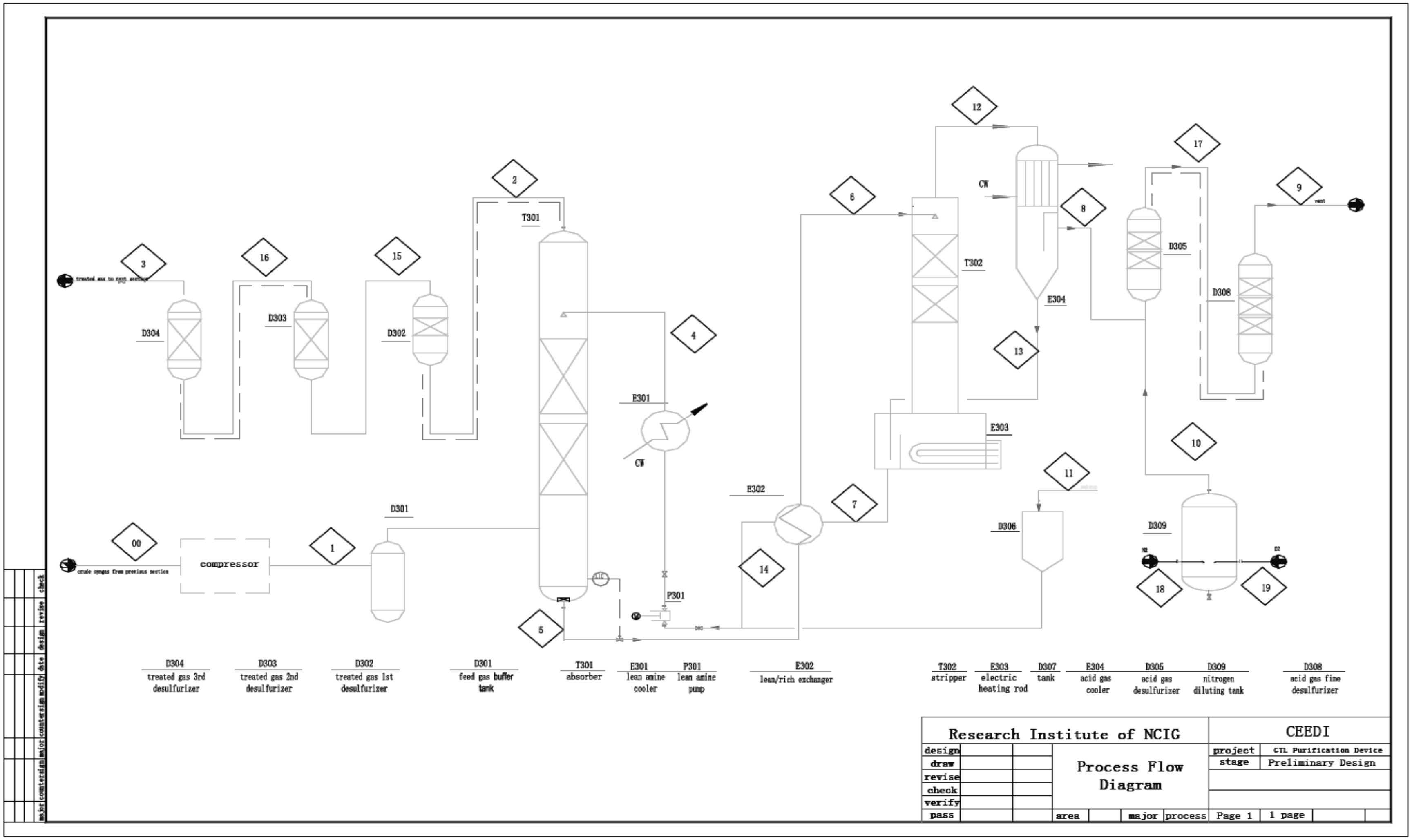

Figure 16: Process Flow Sheet for Acid Gas Cleanup

First, the crude syngas from the gasification section is compressed to 3.0MPag by the compressor (K201), then after the feed gas buffer tank (D301), it is introduced to the absorber (T301) from the bottom, where the syngas contacts counter-currently with the NCMA solution falling from the top. The H_2S and CO_2 are absorbed by the NCMA solution, and the crude treated gas is then discharged from the overhead of the absorber (T301). The crude treated gas out of the absorber (T301) is preheated to 50-90℃, and then proceeds through the three desulfurizer tanks (D302, D303, D304) successively. These tanks are equipped with the COS hydrolysis catalyst and the fine desulfurization agent. Under the hydrolysis catalyst, the COS in the crude treated gas would react with the steam to form H_2S and CO_2. Then the generated H2S is adsorbed by the fine desulfurization agent. After the three desulfurizer units, the total sulfur in the treated gas is reduced to less than 1 ppm, and then the treated gas is sent to the downstream section for further processing and conversion. To ensure the optimal process dynamics, each of the desulfurization tanks is equipped with an electrical heating tape to maintain appropriate temperature in each vessel. The electric heating of D302, D304 and D308 can provide heat during temporary shutdowns, which will prevent the production of condensate.

The rich amine that has been loaded with absorbed CO_2 and H_2S, exits from the bottom of absorber (T301) and proceeds into the lean/rich heat exchanger (E302). This heat exchanger is used to recover the heat of the lean solution exiting the bottom of the stripper (T302) into the rich solution exiting the absorber before the rich solution enters into the stripper. The rich amine flows into the top of the stripper (T302) and contacts with the steam moving upwards from the bottom which liberates a significant portion of the acid gas. Then the rich amine continues to flow down and enters into the reboiler (E303), where the rest of the acid gas is desorbed. The newly lean solution flows from the bottom of the stripper back through the lean/rich heat exchanger before it is pumped to the lean amine cooler (E301) by the lean amine pump (P301). Finally, the cooled lean amine solution flows to the top of the absorber where the process repeats. The round trip circulation of the solution constitutes the process of continuous absorption and desorption for constant acid gas removal. The required heat for the liberation of the acid gas is provided by the electrical heating rod (E303).

After the acid gas is liberated in the stripping column, the desorbed gas flows from the overhead of the stripper to the acid gas cooler. Here the gas is cooled and the condensed water is recycled to the reboiler (E303). The dehydrated acid gas is then introduced into the acid gas desulfurization tank (D305) that uses the activated carbon sorbent to remove most of the H_2S. A mixture of O_2 and N_2 are introduced into the acid gas desulfurization tank to provide the required oxygen for the desulfurization reactions. Upon the removal of most of the H_2S, the acid gas is heated to 50-90℃ by electric heat trace and introduced into the fine desulfurizer (D308) that contains COS hydrolysis catalyst and additional activated carbon sorbent. In this tank the COS hydrolysis catalyst first hydrolyzes the COS to H_2S and H_2O, and the active carbon sorbent adsorbs the H_2S. This is done to ensure the total sulfur of the tail gas is less than 10 ppmv per the downstream requirements. After the desulfurizer, the tail gas is discharged to the flare.

To maintain the water balance of the system, makeup water is required under normal operating conditions, as the water leaving in the treated gas and acid gas is more than that brought in by the feed gas. When the water brought into the system by the feed gas increases, the amount of the makeup water will be reduced. When the water brought into the system by the feed gas is more than that brought out by the treated gas and acid gas, the drain line of the acid gas cooler will be used to discharge the water into the tank or the underground tank to maintain the water balance of the system. When the acid gas in the lean solution is more than 3.25mol%, it suggests that the amine solution needs to be replaced.

Since the system is not only a pilot plant but also a piece of equipment to use for fundamental research, the unit comes equipped with 6 sampling ports for laboratory analysis, including sampling for:

- Feed gas into the system (AP301);

- Treated gas out of the system (AP302);
- Tail gas out of the system (AP305);
- Lean amine (AP303);
- Rich amine (AP304); and
- Crude treated gas out of the absorber (AP306).

BALANCE OF PLANT, SAFETY FEATURES AND HAZARDS & OPERABILITY

Through our participation in Environmental Assessments [EAs] and Hazards and Operability [HAZOP] reviews, the project team examined closely the specific processes and equipment that will operate, with respect to all their requirements from inputs to outputs of feed materials, to good product and waste streams, to environmental, safety and occupational health. The review encompassed the design, construction, and operation of the "upstream" units of the facility, specifically, the coal handling, gasification, and acid gas cleanup components. The team examined the construction of associated equipment platforms and installations, and operation of the refinery. The review covered the breadth of processes, equipment, feed and waste streams, accident scenarios and safety issues. Moreover, the assessments informed us about important considerations for maintaining the cordial relationships that we've always enjoyed with adjacent property owners and the community with respect to area proximity noise, odors and light-emitting sources, such as for example that related to the operation of a flare for the facility.

In addition to the equipment and processes described previously, the facility has significant auxiliary components [Figure 17 below] including a nitrogen generator, air compressor, chiller system, oxygen tank, safety fans, 15 ton crane, natural gas supply, and flare system to completely combust any gas leaving the system. Safety features are integrated into the design of the gasifier and gas cleanup systems. Among other features, the facility has numerous gas leak detection monitors and the facility has large fans that can quickly vent the entire building to remove unsafe gases should a leak occur. The fans and gas monitors are incorporated into the control system to create a safe operating environment. The flare system is be a self-supporting structure, made up of three primary components: the flare stack, the flare tip, and the ignition system. The flare stack height is designed to be 15 feet with a 3 inch diameter flare. The flare manufacturer, GBA-Corona, Inc., designed the stack height based primarily on thermal radiation at grade elevation, such that the thermal intensity would be insufficient to cause discomfort for long exposures to people at any distance from the flare at ground level (GBA-Corona 2013). Further, for safety purposes, the flare system includes a detonation arrestor to protect the header in the event of a flashback within the flare stack.

Figure 17: Photo – O2 Tank, Compressor, N2 Generator, Crane, Safety Fans, Chiller, Flare.

SHAKEDOWN AND COMMISSIONING OF UPSTREAM SECTIONS

A. Coal-Water Slurry Feed Preparation Section

Before full gasification operation could commence, a suitable coal water slurry (CWS) was prepared and analyzed. During the testing phase, it was determined that the mill needed some minor modification to work properly which included adjusting the slurry path. Another important component of the coal preparation system is the coal weight feeder, which was also tested and calibrated before use.

To make the CWS, coal was loaded into the hopper at the top of the coal preparation system using the attached crane. From there, the coal is fed into the weight feeder and then added to the mill at the set rate. In the mill, the coal is pulverized, mixed with water, and blended with an additive (Daracem 55) to reduce viscosity and increase dispersion of the coal particles. The properties of the raw coal (as received), additive and the prepared CWS are shown in Table 1Table 1, Table 2 and Table 3, respectively.

Proximate analysis (wt%)				Ultimate analysis (wt%)					Ash fusion temperature (℃)			
M	Ash	V	FC	C	H	N	S	O	DT	ST	HT	FT
1.59	7.3	34.7	56.4	75.02	5.05	1.66	1.51	9.46	1110	1281	1353	1382

Table 1: Raw Coal Composition (dry basis)

Component	wt%
Calcium Lignin Sulfonate	20
Sulfite Liquors	15
Calcium Nitrate	14
Triethanol amine	1
Water	50

Table 2: Additive composition

Average particle size (μm)	Mass concentration	Viscosity (mPa·s)
<50	<60%	<250

Table 3: Properties of CWS

B. Gasification Section

Initial work for preparing the gasifier required preheating the gasifier internals to fully bake out the refractory lining. The preheating work was conducted based on the preheating manual, and the temperature-time curve was precisely controlled during the work. Figure 18 shows a picture of the operating system during the preheating process with a view of the gasifier internals, while Figure 19 shows the temperature data exported from the Delta-V system over the course of the campaign.

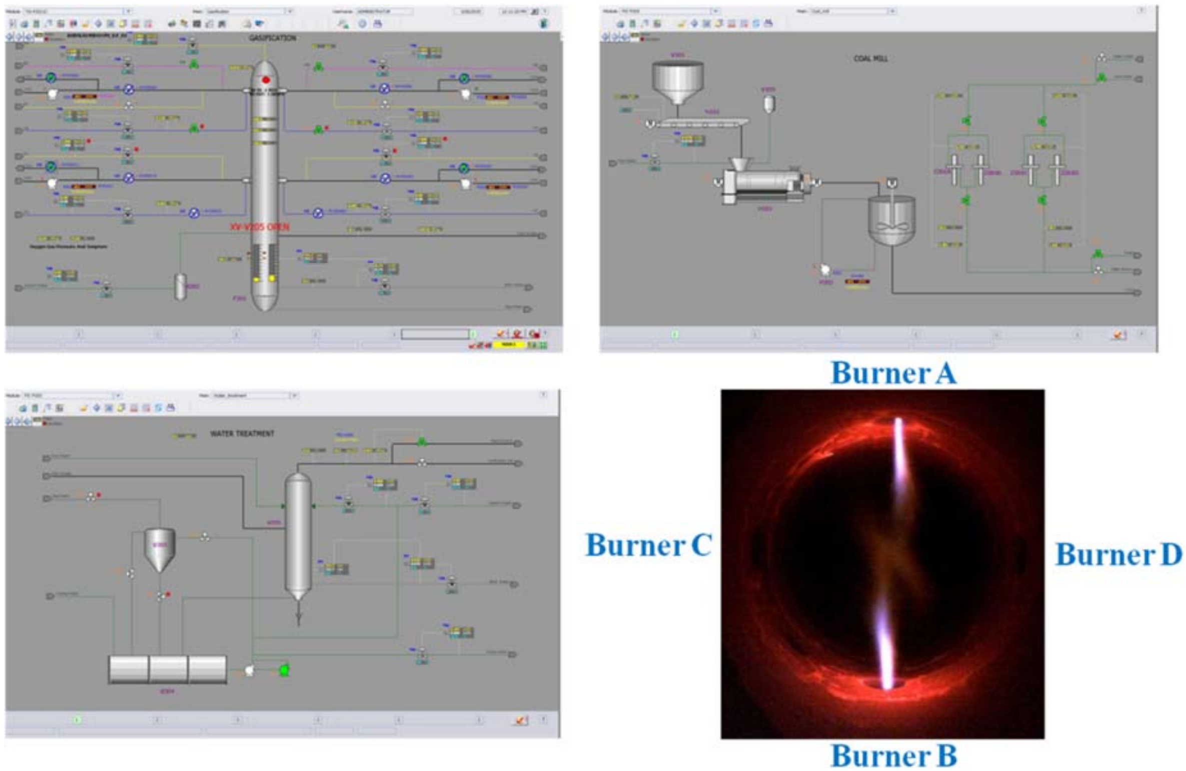

Figure 18: Control System screens with picture of live feed of gasifier internals during preheating

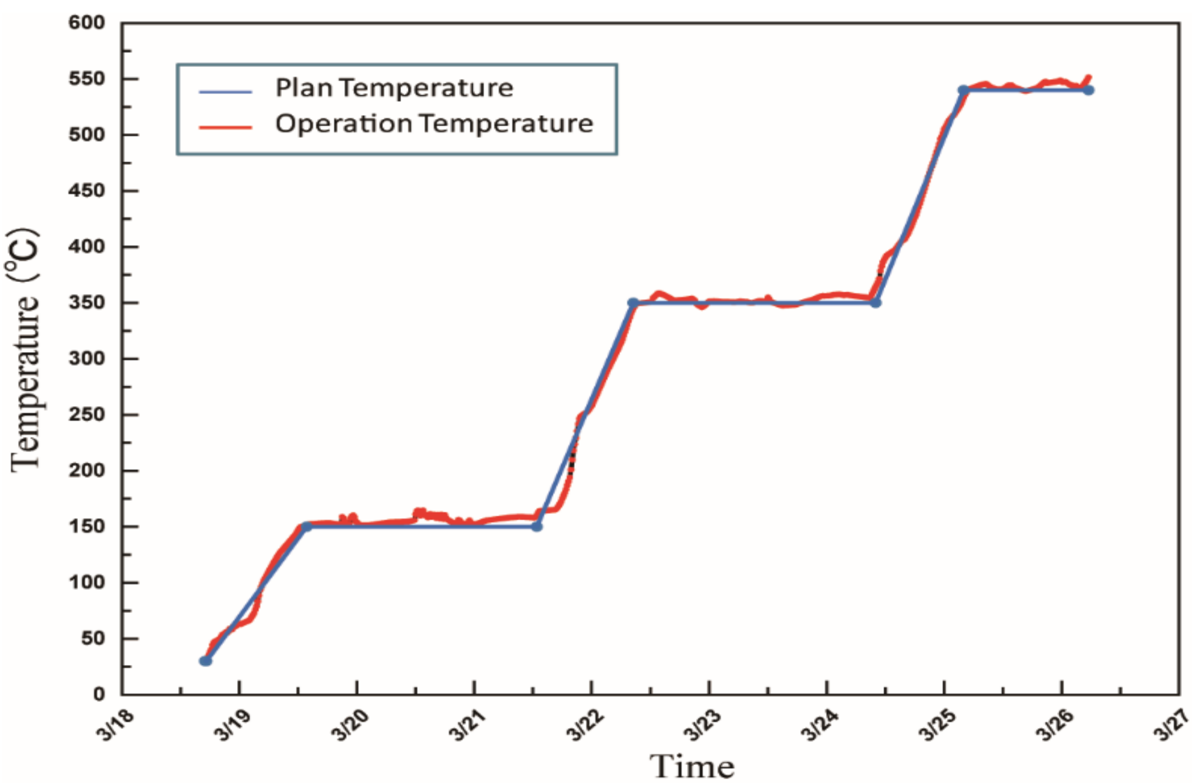

Figure 19: Preheating temperature/time data for preheating of gasifier

The test run of the gasifier was carried out in April 2015. Operation included approximately one day to make enough CWS to run the system, 18 hours to heat the system to gasification temperatures and then about 6 hours of gasification testing. The gasification testing itself began once the temperature inside the gasifier reached 900 ºC. Ideally, gasification would be performed at 1200-1500 ºC, however since this was the first gasification test a lower gasification temperature was used. Once at temperature, burners C and D were used to inject the prepared CWS while still burning natural gas to maintain the temperature. During this time, oxygen rates were kept high to maintain full combustion of the natural gas and keep the gasifier temperature stable. Once the reactor conditions were more stable (approximately 1 hour), the natural gas flow from burners A and B were shutdown. Also, during this time oxygen flow rates were lowered so that gasification could be performed. At this point only coal gasification from burners C and D were operational. After another stability test period of approximately 1 hour, burners A and B also began injecting CWS. At this point, full gasification from all four burners using their full capacity was performed. The system maintained the full gasification reaction with no problems.

After 3 hours the system was shut down in the interest of safety, mainly because the camera system used to monitor the flame and internals of the gasifier began to get blurry. This was caused by the moisture and particulates in the system sticking to the lens. It should be noted here that the system was operating completely normal and could have continued to run without the camera system; all components of the gasifier operated as expected and each piece of equipment performed perfectly. The operation data of gasification process is shown in Figure 20 below. The total gas flow of 250 lb./hr. (55Nm^3/hr.) was slightly higher than the value of 179 lb./hr. expected from the simulation, due to the addition of nitrogen to protect the camera and ignition system. The nitrogen flows are used to keep the camera lens clean and also keep particles from entering the ignition rod. Further investigations of the synthesis gas were performed using gas samples taken during the experiment and subsequently analyzed. These results indicate that the synthesis gas being produced was approximately 44 mol% CO_2, 23 mol% CO, and 18% H_2. This corresponds to an H_2/CO ratio of 0.78 which is very close to the simulation expectation of a 0.75 ratio. The minor difference can be attributed to experimental variations and shortcomings of the simulation models.

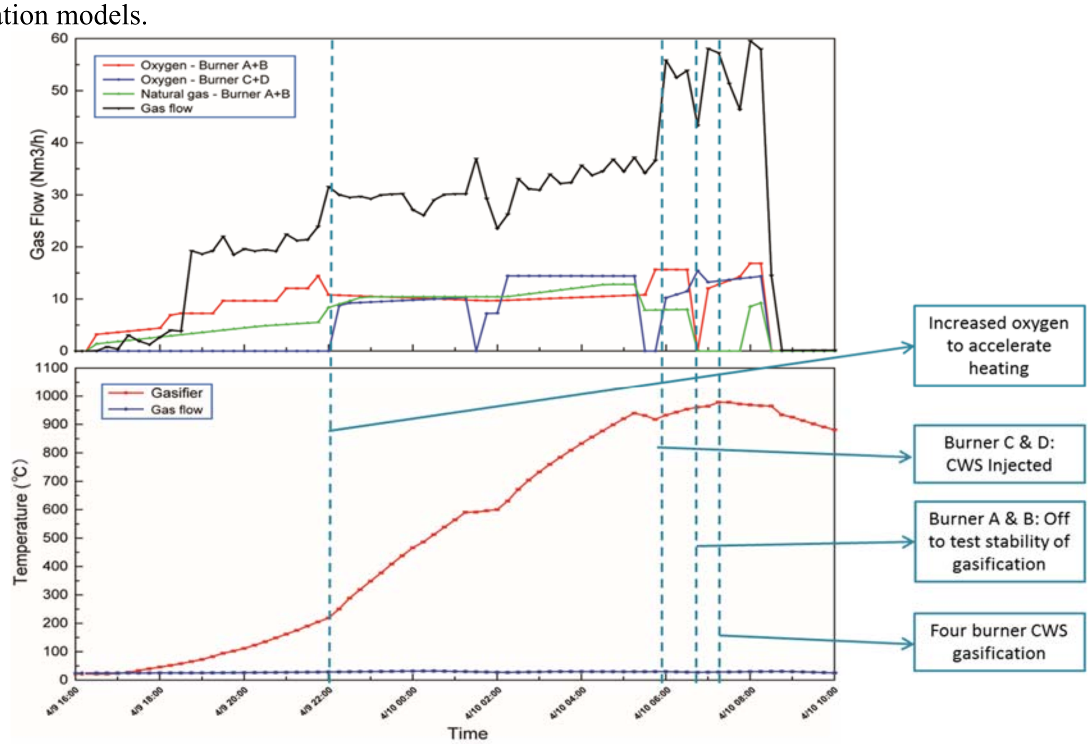

Figure 20: Gasifier operating data during commissioning

C. Acid Gas Removal [AGR] Section

All of the piping and controls work were finished while some issues with the electric components delayed the installation work. The feed pipes to the acid gas plant were welded to the gasifier and syngas compressor, and the outlet welded to the flare line. Similarly, all interconnecting pipes are finished. The last of the piping work is finished, which included all of the auxiliary connections: cooling water in, cooling water out, nitrogen, compressed air and oxygen. Upon completion of the piping work, leak checking and mechanical testing began in earnest and included all auxiliary piping. Occurring simultaneously to the piping work was the controls work. This consisted of running the connecting cables for all 64 remote input/outputs and subsequently terminating them at the proper location on the programmable logic controller (PLC).

Although the controls wiring was fairly straightforward, it was during this time that UKY-CAER began to notice some irregularities with the electrical design and components provided by its Chinese contractor. While it appeared the controls were designed to American standards with respect to quality and completeness, there were significant problems with the electrical design. In addition, with a process/plant of this scale there is a significant overlap between the controls design and the electrical design. In an attempt to rectify this problem CAER contracted ZETON to finish the controls/electrical work, to assure that they first met UL standards, but also so that the AGR controls are completely integrated and compatible with the rest of the refinery's main DeltaV control system. This will allow full integration of all processes upstream and downstream, and will provide important synergies with respect to cost, labor and functionality.

Other work that occurred with respect to the acid gas plant included loading chemicals into the system, and chiller startup/integration. The total chemical loading process took a little over two weeks to complete and consisted of over 200 total bags of chemicals loaded into the tanks (over 10,000 pounds). Chiller startup and integration went very smoothly. After all the pipes were run, the system was leak checked. After a couple small leaks were repaired the 50:50 solution of water/glycol was added to the system. It was then turned on and ran for over 3 days without any complications.

CONCLUSIONS

Since 2007, UK with support of DOE has pursued the tangible construction and development of a coal/biomass-to-liquids facility at the larger capacity of 1bbl./day. Such a facility has required significant lead time for environmental review, architectural/building construction, and EPC services for the design and fabrication of the principal refinery units. UK and DOE have made a substantial investment of time and money to bring this facility to reality – and have advanced the project in several important ways. These include: a formal EA/FONSI, and permits and approvals; construction of a building to house the refinery; selection of a range of technologies and vendors; and the design, fabrication and installation of upstream process units for feed handling, gas cleaning, conditioning and compression, and gasification. Additional capital resources, provided under a separate DOE award, will finish out initial capitalization of the facility with the addition of downstream units for water-gas-shift and Fischer-Tropsch synthesis and the associated BOP - and provide for a working mini-refinery at a 1bbl./day capacity.

As a first task UK contracted a competent EPC company to conduct a detailed engineering design of the downstream refinery units to determine technical requirements and to arrive at a more accurate financial estimate. Key modifications to the design have occurred over time to better suit DOE and the state of Kentucky's objectives, and to achieve cost savings. Modifications in the design have included:

- The switch from the auto thermal reforming of natural gas to coal-biomass gasification came out of DOE's 2010 peer review recommendations. [This was a right and appropriate decision as it greatly increased the efficacy of the facility: coal gasification and the related deep gas clean-up processes represented fruitful fields of future investigation and our facility could now be used for both investigations of upstream gasification and downstream refining].
- Cost savings from the foreign-sourcing of a greatly less expensive and proven gasifier than that which could be sourced domestically, including all the associated coal handling and preparation equipment. The foreign-bought gasifier system was even less expensive than a relatively simple and proven but domestically-sourced natural gas ATR.
- Cost savings from the foreign-sourcing of a greatly less expensive deep clean-up acid gas removal [AGR] plant needed for relatively more dirty coal and biomass feeds, that was even less expensive than a relatively simple but domestically-sourced light gas clean-up system for natural gas.
- Cost savings from the change from an expensive slurry-bed bubble column [SBCR] F-T reactor to a less expensive Micro-channel F-T reactor, including the related investment in the BOP.

The major deliverables of this project were the completion of the plant building, auxiliary process systems (nitrogen, oxygen, chiller, flare, etc.), and the upstream units for gasification and acid gas cleanup, conditioning and compression. To that end, these deliverables have been completed and the current upstream process units are operational. Upon completion of the downstream process units, a fully functioning 1bbl/day coal to liquids facility will then be operational. However, in addition to the physical hardware and process units, this project provided the opportunity to study process scale-up and integration issues. These lessons provided a significant learning opportunity in the development of a coal-to-liquids facility and were an important product from this project. Lastly, significant work and resources were incorporated to assure the long-term viability of the facility, including its future repurposing.

FUTURE OF FACILITY

AVAILABLE FOR A RANGE OF RESEARCH AND INVESTIGATIONS

With respect to research at this facility, it is expected to be used for a range of investigations related to: Feed Preparation, Characteristics and Quality; Coal and Biomass Gasification; Gas Clean-up/ Conditioning; Gas Conversion by FT Synthesis; Product Work-up and Refining; Systems Analysis and Integration; and Scale-up and Demonstration. The facility is also intended to produce research quantities of FT liquids and finished fuels for subsequent Fuel Quality Testing, Performance and Acceptability. Environmental Considerations - particularly how to manage and reduce carbon dioxide emissions from CBTL facilities and from use of the fuels - will be a primary research objectives. A more detailed description of each of these research areas can be found in APPENDIX 2: FACILITIES CAPABILITY AND RESEARCH PLAN.

The deliverables from the operation of this pilot plant will be firstly the liquid FT products and finished fuels, which are of interest to UK-CAER's academic, government and industrial research partners. Furthermore, it will be a test platform to take lab scale work to the next level of scale-up and to have a fully integrated, continuous synthesis gas to final products proof-of-concept facility. Constituting a true process development unit, it will enable different catalyst formulations, gas compositions, temperatures and pressures as well as recycle optimizations to be done. The facility will carry out research on synthesis gas (syngas) derived from coal and coal-biomass gasification. Important areas of investigation will include gas cleaning and conditioning to assure the necessary syngas quality for FT synthesis. Research would include experiments on water-gas-shift and Fischer-Tropsch processes as well as on catalyst structure-function properties with the ultimate goal of reducing the costs of the process and helping produce a more environment-friendly liquid fuel using abundant domestic feed resources.

On an on-going basis, the know-how, show-how associated with the facility is expected to be a key benefit, which can be used as test beds for new technologies and concepts at a level of expenditure that is affordable. It will provide open-access facilities and information in the public domain to aid the wider scientific and industrial community, and a means to independently review vendor claims and validate fuel performance and quality.

The facility will be used to build up human capital – the future generation of skilled energy technologists, engineers and operating personnel that will be needed to sustain a CBTL industry. One of the best ways of creating this skills base is to stimulate and fund RD+D at appropriate institutions which have the facilities to teach and train students in the practical application of science and engineering.

MODULARITY AND FLEXIBILITY FOR FUTURE RE-PURPOSING

The facility has been purposely designed as modular, skid-mounted, anticipating frequent change-outs; "plug and play"; and future re-purposing. In this respect, the gasifier was purposely designed to provide twice the flows needed for the FT refinery section to accommodate other slipstream studies; that being at a capacity of 2 bbl. /day output [1 ton coal-biomass feed/day; 179 lb./hr. total flow; 65 lb./hr. CO; 3.49 lb./hr. H2]. For research purposes the gasification process can be run in a range of 40-120% of the rated capacity which provides the ability to ramp up/down and provide slipstreams for multiple downstream units. The facility has been designed to permit maximum flexibility and to view this gasification facility as a potentially important syngas production facility for a variety of complimentary research, including, for example, as a mid-capacity test facility for first-of-kind carbon capture technologies. Figure 21 shows an artist's rendering of the facility of the future.

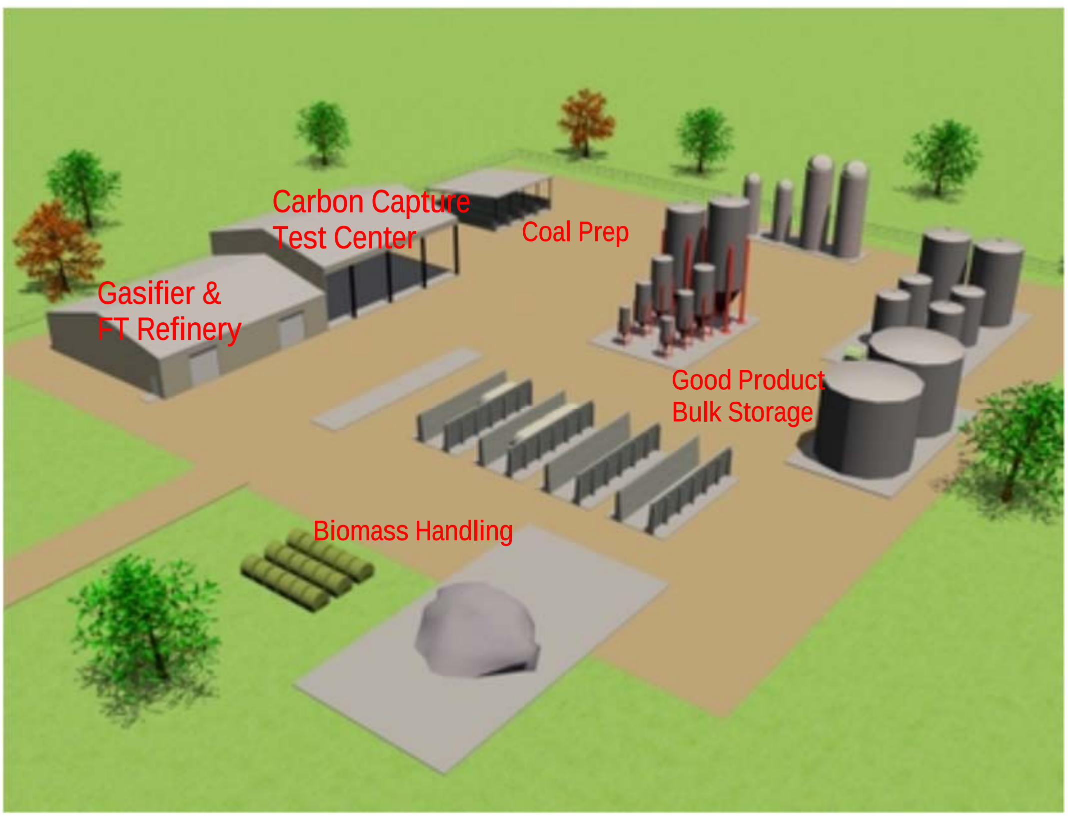

Figure 21: Artist's rendering - Facility of the Future

GRAPHICAL MATERIALS LIST

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LIST OF ACRONYMS AND ABBREVIATIONS

ECUST: East China University of Science and Technology
UK-CAER: University of Kentucky – Center for Applied Energy Research
CEEDI: China Electronics Engineering Design Institute
OMB: Opposed Multi-Burner
P&ID: Piping and Instrumentation Diagram
CTL: Coal to Liquids
CBTL: Coal/Biomass to Liquids
FT: Fischer-Tropsch
CFA: Coal Fuel Alliance
FEED: Front End Engineering Design
RD+D: Research, Development and Demonstration
PDU: Process Development Unit

APPENDICES

APPENDIX 1: FACILITY PROFILE

FACILITY PROFILE

Mini-Fischer-Tropsch Refinery: Coal/Biomass-to-Liquids Process Development Unit (PDU)

University of Kentucky Center for Applied Energy Research
DOE Agreements FC2608NT0005988, FC2612FE0010482

Coal-biomass-to-Liquids PDU

Project Owner
University of Kentucky Center for Applied Energy Research

Plant Design and EPC Services
ZETON, Inc.
China Electronics and Engineering Design Institute [CEEDI]
East China University of Science and Technology, Key Laboratory of Coal Gasification

Architectural & Engineering/ Building Construction
Murphy & Graves Architects
CMTA Engineering
Parco Construction Company

Sponsors
US Department of Energy
KY Energy & Environment Cabinet
University of Kentucky

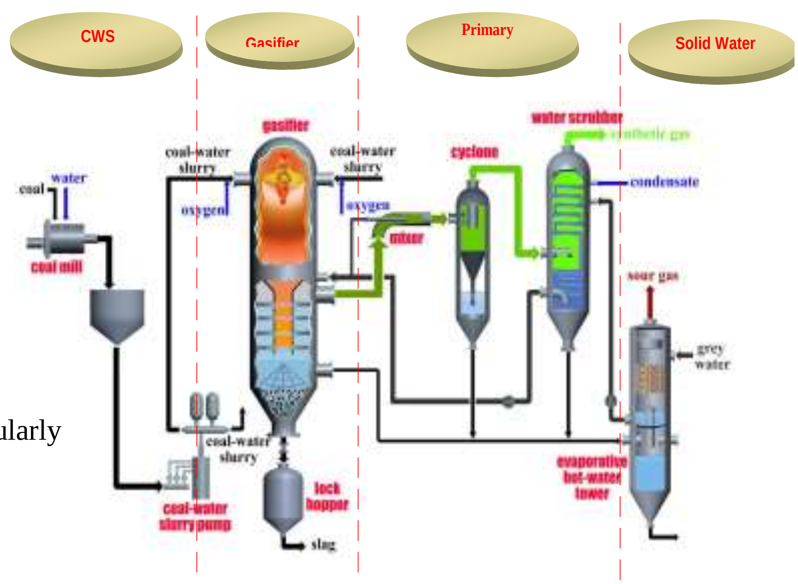
I. VISION FOR FACILITY

The overarching objective of this project is to advance the design, construction and commissioning of an integrated coal/biomass-to-liquids (CBTL) facility at a capacity of 1 bbl. /day at the University of Kentucky (UK-CAER). The university intends to concentrate resources, create a critical mass of expertise, and provide a focal point for RD+D on fuels and chemicals derived from coal and biomass.

On an on-going basis, the know-how, show-how associated with the facility is expected to be a key benefit, which can be used as test beds for new technologies and concepts at a level of expenditure that is affordable. It will provide open-access facilities and information in the public domain to aid the wider scientific and industrial community, and a means to independently review vendor claims and validate fuel performance and quality. The facility will be used to build up human capital – the future generation of skilled energy technologists, engineers and operating personnel that will be needed to sustain a CBTL industry.

II. AREAS OF RESEARCH

- Feed Preparation, Characteristics and Quality
- Coal and Biomass Gasification
- Gas Clean-up/Conditioning
- Gas Conversion by FT Synthesis
- Product Work-up and Refining
- Fuel Quality Testing, Performance and Acceptability
- Systems Analysis and Integration
- Environmental Considerations – particularly the means to manage/reduce CO_2



III. FACILITY DESCRIPTION AND CAPABILITIES

The main unit processes of the current configuration consist of:

- A coal/biomass gasifier for syngas production;
- Water-gas shift reactor for adjustment of H:CO ratio;
- An amine-based stripper/scrubber and carbon bed system for gas cleaning and conditioning;
- A micro-channel reactor for FT synthesis; and
- A hydrocracker to crack the heavier fractions and optimize diesel yields.

The plant complex includes ancillary systems for power generation, utilities, effluent treatment, ash disposal and operating, safety control and monitoring systems. The facility is of a modular design with skid mounted process units – and is intended to be adaptable to change-outs of equipment and capabilities. At present, the planned capacities of process units are:

- Coal/biomass Gasifier (Opposed Multi-burner) design capacity: 1 ton coal-biomass feed/day; 179 lb./hr. total flow; 65 lb./hr. CO; 3.49 lb./hr. H_2;
- Fischer-Tropsch Reactor (Micro-channel) design capacity: 1.0 barrel/day (BPD);
- Hydrocracking design capacity: 0.5 BPD;

IV. FLEXIBILTY AND RE-PURPOSING

The facility has been purposely designed as modular, skid-mounted, anticpating frequent change-outs; "plug and play"; and future re-purposing. In this respect, the gasifier was purposely designed to provide twice the flows needed for the FT refinery section to accommodate other slipstream studies; that being at a capacity of 2 bbl./day gas output [1 ton coal-biomass feed/day; 179 lb./hr. total flow; 65 lb./hr. CO; 3.49 lb./hr. H_2].

Alternate Configuration for Fuels and Chemicals: Natural gas feed; methane reforming

- Natural Gas Auto-thermal Reactor
- Mild Gas Clean-up
- Fischer-Tropsch Synthesis – Slurry Bubble Column Reactor or Micro-channel
- Fluid Catalytic Cracking
- Hydrocracker
- Dehydrogenation Unit
- Alkylation Unit

Mid-scale CO2 Capture Research and Testing Center

Insofar as budget and schedule can tolerate, we have designed the facility to permit maximum flexibility to view this coal gasification facility as a potentially important syngas production facility for a variety of complimentary research, including potentially as a mid-capacity test facility for first-of-kind carbon capture technologies.

APPENDIX 2: FACILITIES CAPABILITY AND RESEARCH PLAN

FACILITY CAPABILITIES AND RESEARCH PLAN

Design and Construction of Early Lead Mini Fischer-Tropsch Refinery: Coal/Biomass-to-Liquids Process Development Unit (PDU)

University of Kentucky Center for Applied Energy Research
FC26-08NT0005988

In Response to Review Panel Action Item 2 (A2), FY11 Advanced Fuels Peer Review, October 18 – 22, 2010
U. S. Department of Energy, National Energy Technology Laboratory

I. Vision of the Facility

The overarching objective of this project is to advance the design, construction and commissioning of an integrated coal/biomass-to-liquids (CBTL) facility at a capacity of 1 bbl/day at the University of Kentucky (UK-CAER). The university intends to concentrate resources, create a critical mass of expertise, and provide a focal point for RD+D on fuels and chemicals derived coal and biomass. The effort will address current unmet needs for CBTL technologies, emphasizing applied and developmental needs.

With respect to research at this facility, Environmental Considerations - particularly how to manage and reduce carbon dioxide emissions from CBTL facilities and from use of the fuels - will be a primary research objective. In addition, the facility is expected to be used for a range of investigations related to: Feed Preparation, Characteristics and Quality; Coal and Biomass Gasification; Gas Clean-up/Conditioning; Gas Conversion by FT Synthesis; Product Work-up and Refining; Systems Analysis and Integration; and Scale-up and Demonstration. The facility is also intended to produce research quantities of FT liquids and finished fuels for subsequent Fuel Quality Testing, Performance and Acceptability [these areas of research are described in some detail in section IV below].

On an on-going basis, the know-how, show-how associated with the facility is expected to be a key benefit, which can be used as test beds for new technologies and concepts at a level of expenditure that is affordable. It will provide open-access facilities and information in the public domain to aid the wider scientific and industrial community, and a means to independently review vendor claims and validate fuel performance and quality. The facility will be used to build up human capital – the future generation of skilled energy technologists, engineers and operating personnel that will be needed to sustain a CBTL industry. One of the best ways of creating this skills base is to stimulate and fund RD+D at appropriate institutions which have the facilities to teach and train students in the practical application of science and engineering.

II. Rationale and Support of DOE Research Objectives

There are significant opportunities for the expanded, diversified use of coal as a means to supplant petroleum in higher value-added markets for transportations fuels, chemicals and advanced materials, particularly when energy security is a driver. The use of coal for the latter purposes can provide additional independence from oil imports, safeguard the nation's security, and allow for the development of new industries. Furthermore, the DOE reports that coal mixed with optimum levels of biomass can reduce the carbon footprint of CBTL fuels processes. A recent National Energy Technology Laboratory (NETL) study indicated that the addition of moderate amounts of biomass to coal for the production of liquids can substantially reduce Life Cycle Analysis (LCA) CO_2 emissions relative to a petroleum diesel baseline. Moreover, the composition of coal liquids differs from that of petroleum, such that there are certain applications where they are environmentally superior, for the production of ultra-clean diesel and jet fuel of interest to the aviation, heavy equipment and trucking industries. The nation's military also have a keen interest in securing alternative battlefield and jet fuels derived from coal and biomass.

Therefore, this project and facility directly supports DOE/NETL's mission of "ensuring the availability of near-zero atmospheric emission, abundant and affordable, domestic energy to fuel economic prosperity, strengthen energy security, and enhance environmental quality". In addition, this facility complements NETL's key focus areas of technologies that will enable 1.) the full realization of the clean-energy potential of the nation's abundant domestic coal supplies, while meeting environmental and climate change goals; and 2.) moving to a hydrogen economy, including hydrogen from coal gasification.

III. Facility Description and Capabilities

The main unit processes of the facility consist of gasification, gas cleaning and conditioning, gas conversion by FT synthesis, and product work-up (refining). The plant complex will also include ancillary systems for power generation, utilities, effluent treatment, ash disposal and operating, safety control and monitoring systems. The facility will be of a modular design with skid mounted process units – and is intended to be adaptable to change-outs of equipment and capabilities. At present, the current configuration of process units includes:

- A coal/biomass gasifier for syngas production;
- Water-gas shift reactor for adjustment of H:CO ratio;
- An amine-based stripper/scrubber and carbon bed system for gas cleaning and conditioning;
- A water-gas-shift reactor for hydrogen production;
- A micro-channel reactor for FT synthesis [although the facility is designed to also accommodate a slurry bed column reactor]; and
- A hydrocracker to crack the heavier fractions and optimize diesel yields.

In addition, although funding is insufficient at the present time, the facility is designed to eventually accommodate additional downstream process units:

- An alkylation unit to improve the octane number of the naphtha fraction and to improve the lubricity and cold temperature properties of the diesel;
- A dehydrogenation unit for paraffin and olefins; and
- A fluid catalytic cracking unit to provide gasoline and diesel cuts for blending.

The capacities of these units follow:

Coal/biomass Gasifier (Opposed Multi-burner) design capacity 91 lb/hour feed, 65 lb/hr. CO;
Fischer-Tropsch Reactor (Micro-channel) design capacity: 1.0 barrel/day (BPD);
Hydrocracking design capacity: 0.5 BPD;
Fluid catalytic cracking design capacity: 0.2 BPD;
Dehydrogenation design capacity: 0.17 BPD; and
Alkylation design capacity: 0.17 BPD.

The deliverables from the operation of this pilot plant will be firstly the liquid FT products and finished fuels, which are of interest to UK-CAER's academic, government and industrial research partners. Furthermore, it will be a test platform to take lab scale work to the next level of scale-up and to have a fully integrated gas to final products continuous proof-of-concept facility. Constituting a true process development unit, it will enable different catalyst formulations, gas compositions, temperatures and pressures as well as recycle optimizations to be done. The facility would carry out research on synthetic gas (syngas) derived from coal and biomass gasification. Important areas of investigation will include gas cleaning and conditioning to assure the necessary syngas quality for FT synthesis. Research would include experiments on water-gas-shift and Fischer-Tropsch processes as well as on catalyst structure-function properties with the ultimate goal of reducing the costs of the process and helping produce a more environment-friendly liquid fuel. Through successful research, the proposed project would help manage and reduce carbon dioxide emissions from CBTL facilities and from use of the fuels and would help to develop facilities and personnel to sustain a domestic coal/biomass-to-chemicals industry.

IV. Areas of Research - Advancing the State of the Art of CBTL

The prospect of CBTL technologies is alluring, but the deployment of new energy technologies bring with them certain technical risks not normally associated with proven technologies. Technical risk can be reduced and deployment stimulated by making investments in research, development and demonstration (RD+D) to reduce the technical hurdles of new energy technologies.

There are a number of issues which, if addressed in creative ways, can alleviate some of the technical risks associated with the adoption of CBTL technology. Over the long-term, research at this facility is expected to advance the state of the art with respect to the following areas of investigation:

Feed Preparation, Characteristics and Quality

The benefits of biomass feed qualities, particularly torrefied biomass added to the pulverized coal will be investigated, including its ability to drive off moisture and volatile compounds, make the biomass more stable, compactable and energy dense and improve grind ability. Research will be performed related to optimizing systems for manipulating feed quality, and for evaluating the performance of biomass as a gasification feed co-mixed with coal.

Coal and Biomass Gasification

Gasifiers suitable for integration with fuel synthesis or hydrogen production can be demonstrated at an affordable scale, including compatibility with emerging coal and biomass feed stocks; vessel design and increased knowledge of bed behavior/agglomeration; and effective process control to maintain gasifier performance and emissions at target levels with varying load, fuel properties, and atmospheric conditions.

Gas Cleanup/Conditioning

Syngas cleaning is an area where there are further opportunities for improvement. This also involves cost reduction and the adjustment of the H2 to CO ratio in the syngas for optimal FT performance. Moreover, gas cleaning and conditioning systems to remove contaminants (tar, particulates, alkali, ammonia, chlorine, and sulfur) not suited to downstream catalysts will be important, as will systems for hot gas particulate removal and advanced desulfurization adsorbents.

Gas Conversion by FT Synthesis

Although the cobalt catalysts (mostly proprietary) have expected lives of up to 5 years, there might be cheaper catalyst formulations with similar life expectancies. For iron catalysts, which are cheaper, the thrust for longer life and cheaper production costs, would also apply. The robustness (mechanical attrition resistance) of catalysts varies a great deal and especially some iron catalysts could be relatively weak, limiting the separation of catalyst and wax. In the FT synthesis, there is great variation possible to fine tune selectivities (such as olefin/paraffin ratios, degree of branching, chain length, level of oxygenates and type of oxygenates and the like). The product spectrum is influenced by a large number of parameters like catalyst characteristics, (reduction/pretreatment, morphology, promoters, mechanical strength etc.), process variables (temperature, temperature gradient, pressure, syngas flow rate, syngas composition, gas purity etc.) as well as reactor design features. The combination of these process conditions determines the conversion and the selectivity pattern for the chosen system. There are no an open R&D facilities where such work can be done at a scale beyond the normal scientific lab scale. Having such a facility or facilities could provide potential project developers with a platform from which to optimize the process for their market needs by integrating the synthesis optimization with the product optimization.

Product Work-up or Refining

The discussion here is restricted to the “Low Temperature” FT since these are the simplest FT plants that are likely to be built first in the US. The primary products from the FT reactor are typically separated by a series of thermal steps to separate products in boiling point fractions analogous to a conventional refinery. The lighter gases can, depending on the level of syngas conversion and the value of the energy in the tail gas, be partially cleaned up for recycle (e.g. water removal) or it can be used as a fuel gas in the plant. In some cases (especially when using a

Lurgi gasifier), the methane in the gas can be separated out and reformed to produce more syngas. Without running through all the cuts which can possibly be recovered and purified, it can be stated that the simplest configuration is likely to be that the light liquids (“naphtha”) can be used either as a petrochemical feedstock or potentially as a gasoline component after significant octane number enhancement through isomerization/alkylation (here research could be applied to improve yields). The next heavier cut would be the “straight run” diesel/fuel oil cut and lastly there will be heavier waxes which can be hydro-cracked to bring the boiling point into the diesel range. Variations would be used to produce different grades of jet fuel. Depending on specifications, hydro-isomerization would also be used to improve the cold temperature properties and lubricity characteristics. In the area of product characteristics, there are likely to be opportunities for analytical method development for simpler and more applicable testing procedures, and collaboration with certification authorities will be desirable. As in a refinery there are usually “polishing” steps and special fractionation and or hydrotreating steps to ensure that all specifications for a particular product grade will be met. Thus special grades of fuels and chemicals can be produced in an FT facility, such as special grades of jet and aviation fuels or other “boutique” fuels and chemical components. This is clearly an area for product-specific R&D based on the FT system and by combining the FT system parameters with a multi-purpose continuous product work-up facility, a very powerful tool for companies interested in making particular products, can be established. The issue of separating and purifying components and fractions from complex streams in an FT facility is part of the challenge to maximize profits. In this area creative and novel separation technologies could be developed to add value to a CBTL venture.

Environmental Considerations

Specific research topics could include the efficient use and re-use of water; beneficial use of the ash from the gasifiers (this will depend on the type of gasifier selected); further improvements of technologies to capture sulfur from the gasifiers as well as from the power plant; improved mercury capture (depending on gas purification process); control of volatile organic components and last but not least optimization regarding potential CO_2 capture from all CO_2 sources in a CBTL facility.

Systems Analysis and Integration

To support the above activities it will be essential to have a systems analysis and integration capability. This can be applied for the work plan itself and also to analyze the components in the process facility. These skills will have to be developed and models will have to be verified against the experimental results to enable initial assessments of scale-up opportunities. The software capabilities to control the integrated R&D facility and to apply process engineering optimization to the operation of the facility and to conceptual process configurations will be an ongoing activity. At a more fundamental level the capability of computational chemistry could be used to assess ways to improve separations and catalysis in various parts of the plant.

Scale-up and Demonstration

The reactor types used commercially (up to 20,000 bbl/d per single reactor) have been fine tuned over a long time and incremental improvements are made continually. Some key factors in reactor design include the hydrodynamics (gas and catalyst dispersion, back mixing, temperature profiles, heat distribution), the withdrawal of the high amount of exothermic heat from the FT reactor, good feed gas distribution (mostly patented technologies), the optimization of recycle streams, the effective recovery of catalyst particles (in fluidized beds in the gas phase and in slurry rectors from the wax), pressure drop (especially for tubular reactors as used by Shell) and catalyst feed and withdrawal systems as might be applicable. Developing and verifying reactor design models become meaningful at reactor diameters above about 2 feet, so that this activity will only be valuable at the larger scale of operation before full commercialization. The products produced in smaller units will nevertheless be typical of FT products. If collaboration with engineering contractors can be established, that could strengthen a RD&D team to focus the R&D on relevant issues which will have an economic impact. Normally design details are protected very well by the technology owners. In a similar way, the expertise for scale-up resides mostly with experienced contractors.

Fuel Quality Testing, Performance and Acceptability

Systematic research on the application of FT fuel in gas turbine and diesel engines is required before FT fuel can become a widely accepted commercial transportation fuel. Thermal and storage stability, cold flow properties, atomization performance, fuel/air mixing, combustion stability, emission performance, compatibility with coatings and elastomers, and lubricity are research topics of significant importance and interest to industry, DOD, and government agencies such as the FAA. FT fuels derived from coal are an attractive alternative in several ways to conventional diesel fuel. They have a higher cetane number which leads to shorter ignition delay and enables retarded injection, both of which lower NO emissions. Furthermore, the absence of aromatic components in the fuel reduces the tendency to form particulate matter. FT fuels also have negligible sulfur content which further reduces the particulate emissions. The absence of sulfur is also a significant advantage in the design of exhaust after-treatment devices. In addition, the use of a zero sulfur fuel offers benefits to the EGR systems of diesel engines due to an elimination of corrosion.

V. Related Facilities and Expertise – UK CAER

Some of related facilities and expertise are described below:

CSTR Autoclave Reactors

Based on previous industrial and DOE-sponsored projects, the CAER has installed twenty one-liter stirred autoclave reactors. These have been operated on a continuous basis during the past 15 years. At one stage they were operated to obtain data for catalyst selection and operational data to support Fischer-Tropsch (FT) runs at the DOE La Porte, Texas pilot plant. The reactors are operated to collect liquid products in traps maintained at different temperatures for primary fractionation. Samples are collected of the various product streams and analyzed using appropriate GC techniques. Wax is also recovered through a filter system and analyzed. Numerous peer-reviewed publications on the catalysis of especially Fischer-Tropsch reactions have been made based on work in these reactors.

Slurry Bubble Column Reactor (SBCR) Pilot Plant

The Prototype Integrated Process Unit is a pilot plant system built in the early 1980s for studying a multitude of synthetic fuel/chemical processes. Recently, a direct coal liquefaction reactor within the pilot plant was reconfigured as a SBCR for FT synthesis studies. Initially the reactor did not contain a wax separation system for smaller catalyst particles and a slurry accumulator and a batch wax filtration system were installed. The plant was subsequently redesigned to incorporate automatic slurry level control and wax filtration systems. These design changes allowed for a more constant inventory of the catalyst to be maintained in the reactor while reducing slurry hold-up in the catalyst/wax separation system. The wax filtration system can accept a variety of filter elements. Reactor operation is stable and long-term tests can be conducted to study catalyst deactivation and attrition under real-world conditions. This unit has a nominal capacity of about 1 gallon per day. A complete process description can be provided if required.

Fixed Bed Reactors
Additionally a supercritical fixed-bed reactor (operated for FT) and at least 5 other fixed bed reactors are available for FT and other catalytic systems.

Catalyst Preparation
The CAER has equipment for catalyst preparation of kilogram size samples on a routine basis. For the DOE La Porte FT run CAER personnel prepared a 160-pound catalyst batch using a continuous precipitation method. The catalyst slurry (2,000 pounds) was transported to Süd-Chemie, Inc. in Louisville where it was spray dried for use.

Catalyst Characterization
Most of the major equipment for catalyst characterization is readily available at the CAER. Additionally some characterization can be carried out at the DOE National Laboratory at Brookhaven, New York. Other microscopy characterization is carried out at the UK Center for Advanced Microscopy. Facilities available include: Zeton Altamira AMI-200 Characterization system; Micromeritics Tri-star System; Nicolet Nexus 870 FTIR Spectrometer with Spectrotech high temperature/high pressure cell; Nicolet Raman Spectrometer with a Ventacom in-situ flow cell; in-situ EXAFS/XANES spectroscopy cell; Phillips X-pert Diffractometer; SRI 8610C Gas Chromatograph; and (on campus) JEOL 2010F FasTEM high-resolution transmission electron microscope (HR-TEM).

Analytical Capabilities
Without going into details, it can be stated that CAER has proven over more than two decades that it has world class analytical and mass balance capabilities in the area of coal to liquids and chemicals operation. International companies regularly make use of CAER capabilities in running FT reactors for them, providing mass balances and analyzing the products. There is also experience and expertise in the product work-up area, such as in hydrocracking, and gas cleaning.

Related Topics
Besides the above FT facilities, CAER has many years of experience with carbon materials and coal preparation and ash utilization projects. Gas cleaning and combustion projects have been handled in the past and are currently funded. It is also active in environmental catalysis (biocatalysis, NOx and related gas cleaning) and in optimizing hydrogen production via water gas shift catalysis.

APPENDIX 3: LESSONS LEARNED REPORT

LESSONS LEARNED FROM BUILDING AND EQUIPING A UNIVERSITY-BASED RESEARCH-SCALE MINI REFINERY

Design and Construction of Early Lead Mini Fischer-Tropsch Refinery: Coal/Biomass-to-Liquids Process Development Unit (PDU)

University of Kentucky Center for Applied Energy Research FC26-08NT0005988

In Response to Review Panel Action Item R3, FY11 Advanced Fuels Peer Review, October 18 – 22, 2010, U. S. Department of Energy, National Energy Technology Laboratory

Coal-biomass-to-Liquids PDU

Project Owner
University of Kentucky Center for Applied Energy Research

Plant Design and EPC Services
ZETON, Inc.
China Electronics and Engineering Design Institute [CEEDI]
East China University of Science and Technology, Key Laboratory of Coal Gasification

Architectural & Engineering/ Building Construction
Murphy & Graves Architects
CMTA Engineering
Parco Construction Company

Sponsors
US Department of Energy
KY Energy & Environment Cabinet
University of Kentucky

I. VISION OF FACILITY AND PROJECT OBJECTIVE

The overarching objective of this project is to advance the design, construction and commissioning of an integrated coal/biomass-to-liquids (CBTL) facility at a capacity of 1 bbl./day at the University of Kentucky (UK-CAER). The university intends to concentrate resources, create a critical mass of expertise, and provide a focal point for RD+D on fuels and chemicals derived coal and biomass. The effort will address current unmet needs for CBTL technologies, emphasizing applied and developmental needs.

With respect to research at this facility, it is expected to be used for a range of investigations related to: Feed Preparation, Characteristics and Quality; Coal and Biomass Gasification; Gas Clean-up/Conditioning; Gas Conversion by FT Synthesis; Product Work-up and Refining; Systems Analysis and Integration; and Scale-up and Demonstration. The facility is also intended to produce research quantities of FT liquids and finished fuels for subsequent Fuel Quality Testing, Performance and Acceptability. Environmental Considerations - particularly how to manage and reduce carbon dioxide emissions from CBTL facilities and from use of the fuels - will be a primary research objective

The deliverables from the operation of this pilot plant will be firstly the liquid FT products and finished fuels, which are of interest to UK-CAER's academic, government and industrial research partners. Furthermore, it will be a test platform to take lab scale work to the next level of scale-up and to have a fully integrated gas to final products continuous proof-of-concept facility. Constituting a true process development unit, it will enable different catalyst formulations, gas compositions, temperatures and pressures as well as recycle optimizations to be done. The facility will carry out research on synthetic gas (syngas) derived from coal and biomass gasification. Important areas of investigation will include gas cleaning and conditioning to assure the necessary syngas quality for FT synthesis. Research would include experiments on water-gas-shift and Fischer-Tropsch processes as well as on catalyst structure-function properties with the ultimate goal of reducing the costs of the process and helping produce a more environment-friendly liquid fuel.

On an on-going basis, the know-how, show-how associated with the facility is expected to be a key benefit, which can be used as test beds for new technologies and concepts at a level of expenditure that is affordable. It will provide open-access facilities and information in the public domain to aid the wider scientific and industrial community, and a means to independently review vendor claims and validate fuel performance and quality. The facility will be used to build up human capital – the future generation of skilled energy technologists, engineers and operating personnel that will be needed to sustain a CBTL industry. One of the best ways of creating this skills base is to stimulate and fund RD+D at appropriate institutions which have the facilities to teach and train students in the practical application of science and engineering.

II. FACILITY DESCRIPTION AND CAPABILITIES

The main unit processes of the current configuration consist of gasification, gas cleaning and conditioning, gas conversion by FT synthesis, and product work-up (refining). The plant complex also includes ancillary systems for power generation, utilities, effluent treatment, ash disposal and operating, safety control and monitoring systems. The facility is of a modular design with skid mounted process units – and is intended to be adaptable to change-outs of equipment and capabilities. At present, the planned configuration of process units includes:

- A coal/biomass gasifier for syngas production;
- Water-gas Shift Reactor for adjustment of H:CO ratio;
- An amine-based stripper/scrubber and carbon bed system for gas cleaning and conditioning;
- A water-gas-shift reactor for hydrogen production;
- A micro-channel reactor for FT synthesis; and
- A hydrocracker to crack the heavier fractions and optimize diesel yields.

In addition, although funding is insufficient at the present time, the facility is designed to eventually accommodate additional downstream process units:

- An alkylation unit to improve the octane number of the naphtha fraction and to improve the lubricity and cold temperature properties of the diesel;
- A dehydrogenation unit for paraffin and olefins; and
- A fluid catalytic cracking unit to provide gasoline and diesel cuts for blending.

The capacities of these units follow:

Coal/biomass Gasifier (Opposed Multi-burner) design capacity: 1 ton coal-biomass feed/day; 179 lb./hr. total flow; 65 lb./hr. CO; 3.49 lb./hr. H_2;
Fischer-Tropsch Reactor (Micro-channel) design capacity: 1.0 barrel/day (BPD);
Hydrocracking design capacity: 0.5 BPD;
Fluid catalytic cracking design capacity: 0.2 BPD;
Dehydrogenation design capacity: 0.17 BPD; and
Alkylation design capacity: 0.17 BPD.

III. PROJECT TASKS AND PROGRESS

Below is a brief description of the principal tasks and UK-CAER's progress to date.

Phase I

Task 1.1 Technology Selection [Status-Complete]. CAER has selected and entered into Confidential Disclosure and other teaming agreements with a variety of technology vendors for each of the current and potential processing units envisioned for the facility, including:

Current Configuration: Coal-biomass feed, gasification.

- Coal-biomass Gasifier **-** East China University of Science and Technology, Key Laboratory for Coal Gasification
- Deep Gas Clean-up – China Electronics and Engineering Design Institute
- Fischer-Tropsch Synthesis – Chart Industries Micro-channel Reactor
- Water-Gas Shift Reactor – CompRex, LLC/Robinson Metal Inc. [under license to Chart Industries]
- Hydrocracker – CompRex, LLC/Robinson Metal Inc. [under license to Chart Industries]

Alternate Configuration: Natural gas feed; methane reforming

- Natural Gas Auto-thermal Reactor [ATR] – UNITEL Inc.
- Mild Gas Clean-up, ZETON, Inc.
- Fischer-Tropsch Synthesis – Rentech Slurry Bubble Column Reactor [SBCR] and Velocys Micro-channel FT Reactor
- Fluid Catalytic Cracking – W.R. Grace
- Hydrocracker - UOP
- Dehydrogenation Unit – UOP
- Alkylation Unit - UOP

Task 1.2 FEED Study for the Alternate Configuration [Status-Complete]. Key technical information for each unit process of the alternate process configuration was provided to CAER’s principal EPC contractor, ZETON Inc., for use in completing a FEED Study. The FEED Study firmed up the process design and led to the development of Process & Instrumentation Designs (P&IDs). Zeton, Inc. investigated the optimal skid layout to accommodate the equipment and process units, and suggested an appropriate control system based on its experience. Zeton also provided a +/-10% cost estimate and a more precise schedule for the detailed design, procurement and construction phase of the project.

Task 1.3 A&E Plans and Specifications for Refinery Building [Status-Complete]. CAER engaged the A&E company, Murphy Graves Architects, assisted by CMTA Engineering, to provide design and engineering services related to the general site work, building shell, materials of construction, thermal and moisture control, heating, air conditioning and ventilation, fire protection, finishes, equipment, furnishings, special construction, conveying systems, lighting, mechanical, electrical, plumbing [MEPs], and energy efficiency, and special building utility services for the refinery building.

Task 1.4 Construction of Refinery Building [Status-Complete]. Following receipt of the A&E Plans and Specs, CAER engaged Parco Construction Company for construction of the refinery building. Ground was broken in November 2011, and a Certificate of Substantial Completion and Beneficial Occupancy was issued July 2012 for the facility.

<u>Phase 2</u>

Task 2.1 Cost Estimation & Feasibility Study for Incorporation of Coal Feed Handling and Preparation, Coal Gasifier and Gas Cleaning/Conditioning and Compression Sections [Status-

Complete]. UK CAER engaged Zeton, Inc. for completion of another Cost Estimation & Feasibility Study for potentially incorporating an experimental coal-biomass gasifier and the necessary feed handling and preparation, and gas cleaning/conditioning and compressions sections. A range of gasifiers - Conoco-Phillips, KBR, GE-Texaco, Sasol-Lurgi, Shell and others - were investigated. Some OEMs declined to design and fabricate at this small capacity of 1 bbl./day needed for research purposes; others tendered estimates upward of $10M+ for the gasifier only. The eventual recommendation from ZETON was to procure Future Energy Resources Corporation's [now Rentech's] SilvaGas^{TM} biomass gasification process at a cost estimate of $5.5-5.9 million. At this point, a decision was made to go with a much less expensive and potentially more reliable Chinese-made coal-biomass gasifier for reasons of expense and compatibility with the research-scale needed for this application.

Phase 3

Task 3.1 Fabricate and Install Opposed Multi-Burner (OMB) Coal Gasifier Section [Status - Equipment Received and Currently Being Installed]. CAER procured the design services of East China University of Science and Technology, Key Laboratory for Coal Gasification for a modular Chinese-made opposed multi-burner (OMB) entrained-flow coal gasifier capable of generating synthesis gas sufficient for production of 1 bbl./day products. The main equipment includes: 1.) coal water slurry preparation system (mill, CWS tank, additive container); 2.) raw material supply system (CWS pump, dewar tank, flow meters, oil tank and pump); 3.) gas purge and protection system; 4.) gasification section (stainless gasifier, refractory brick, slag container, burner); 5.) flame monitoring system; 6.) gas composition and temperature analysis system; and 7.) emergency control and shutdown system. The coal-biomass feed system, gasifier and ancillary equipment were subsequently fabricated in China and delivered in December 2013. Installation of the gasifier and balance of plant [BOP] is on-going but nearly complete.

Task 3.2 Fabricate and Install Syngas Work-up and Conditioning and Compression Section [Status – Design Complete, Equipment Currently Being Fabricated, Receipt anticipated September]. CAER procured the design-build services of the Chinese EPC firm, China Electronics and Engineering Design Institute [CEEDI] for a detailed design of a Syngas Work-up, Conditioning and Compression system that will be compatible with the OMB gasifier section. This equipment is currently being fabricated in China. The design/fabrication includes skid-mounted units, with piping and tubing isometrics, a complete structural design, vessel design, detailed electrical conduit and wiring drawings, detailed instrument conduit and wiring drawings, detailed utility drawings (air, steam, cooling water, BFW, and N2), module interface specifications for process flows and safety relief flows and major equipment. Delivery and installation of the equipment is anticipated for September-December.

Task 3.3 Shakedown and Commissioning of Opposed Multi-Burner (OMB) Coal Gasifier Section and Syngas Work-up and Conditioning and Compression Section [Status - Pending]. Once installation of the gasifier and acid-gas clean-up plant is complete, CAER will shakedown and commission the OMB Coal Gasifier, Syngas Work-up and Conditioning and Compression section over a period of months. This task remains to be complete and is anticipated to be finished during the months of January to June 30, 2015.

IV. LESSONS LEARNED

Laboratory facilities, and particularly research-scale pilot plants, are complex, technically sophisticated, and mechanically intensive structures that are expensive to build and to maintain. The design and construction of such facilities come with certain risks that must be managed – ranging from quality and safety, cost management, time management, scope and change management, procurement and contracts, people management, information management, and external influences such as regulatory compliance and community relations. Hundreds of decisions must be made before and during new construction - decisions that will determine how successfully the facility will function when completed and how successfully it can be maintained once put into service. These decisions will also determine whether the project comes in "on time" and "on budget".

Selection of Technologies, Vendors and EPCs: Special Challenges of Research-scale Facilities

A CBTL plant, whether a research scale pilot plant or a commercial plant, is comprised of a number of individual process steps which need to operate in harmony to ensure continuous and integrated operations. Research scale pilot plants pose particular challenges with respect to critical flows and requirements that need specialized, scale-specific knowledge and expertise to simplify the design and lower the capital cost; one reaches diminishing returns for a completely integrated pilot plant, such that some operations should remain batch-operated. It is therefore critical that adequate consideration be given to the selection of technologies and technology vendors. The chosen suppliers of technology should provide the needed warranties that their plants will perform as agreed, but warranties should also be obtained for the overall configuration. Such wrap-around warranties [or "wraps"] are hard to obtain since few such plants have yet been commissioned and operated in the USA at any scale.

The best alternative is to select a reputable engineering, procurement and construction company (EPC) with related experience and in-depth understanding of the technologies to be incorporated in the plant. Moreover, for research scale plants, it is important to consider an EPC contractor that is a leading designer and builder of innovative lab scale systems, pilot plants, demonstration plants and small modular commercial plants. These considerations extend to, besides the main gasification and FT sections, to other parts of the plant, including feed preparation and conveyance, gas cleaning, solid and effluent treatment/disposal, Environmental Assessments and permitting, evaluations of hazards and operability [HAZOP], and logistics regarding feed and products transportation.

Design Pilot-plant Buildings for Flexibility and Re-purposing, Not Equipment Specificity

Normally, in the process of building support and interest in a project of the type described here – to give it clarity and to help with early cost estimating – the developers will have conducted FEED studies of particular plant configurations. With financial resources provided by the Commonwealth of Kentucky, CAER conducted such a Cost Estimation and Feasibility Study. And, for reasons of the ease of use in a university research setting, the logistics of moving large volumes of gases by tube truck and other reasons, our FEED study suggested a natural gas feed, reformed by ATR, as the best means of producing large volumes of synthesis gas for research purposes. From there, we spent significant time designing these specific process units and the BOP – and then designing a special purpose building to suit or "fit" this equipment. In so doing this, our efforts were aimed at minimizing schedule and cost risk. However, the problem with this approach is that it failed to contemplate a change in project direction and/or re-purposing of the facility after completion of certain technology evaluations.

Such a change in project emphasis occurred midway through the project when UK-CAER and DOE mutually agreed to not pursue fabrication of a natural gas ATR and the related equipment and instead to pursue a coal-biomass fed gasification system. Methane reforming is a proven technology with little research benefit other than as a source of synthesis gas for downstream refinery and related investigations – the main focus of this project. Notwithstanding, coal gasification and the related deep gas clean-up processes represented a fruitful field of future investigation and research; our facility could now be used for both investigations of upstream gasification and downstream refining. In the process of redesigning the building to accommodate a gasifier, the capacity of the building had to be more than doubled [from approximately 3000 to 6000 square feet] – and its costs increased appreciably. This increase in the facility's footprint and the change to coal-biomass gasification also necessitated a need to re-visit the earlier Environmental Assessment and Finding of No Significant Impact [FONSI] – and resulted in conducting a full-blown EA Supplement. This led to additional delays and schedule slip, and from time to time put UK-CAER in the position of operating at risk. In all of this, however, our mind set has changed to think modular, skid-mounted; frequent change-outs; "plug and play"; and future re-purposing. Moreover, it has changed us to think maximum flexibility, insofar as budget and schedule can tolerate, to view this coal gasification facility as a potentially important syngas production facility for a variety of complimentary research, including potentially as a mid-capacity test facility for first-of-kind carbon capture technologies. In this respect, the gasifier was purposely designed to provide twice the flows needed for the FT refinery section to accommodate other slipstream studies; that being at a capacity of 2 bbl./day gas output [1 ton coal-biomass feed/day; 179 lb./hr. total flow; 65 lb./hr. CO; 3.49 lb./hr. H_2].

Allow Ample Time for NEPA-EA, Permit Approvals, ESH and HAZOP Evaluations

UK-CAER's research campus might very well be among the best studied 125 acres in Fayette County, Kentucky, having been the subject of numerous Environmental Assessments and Supplements over the years as our facilities have expanded. These EAs are critically needed to gain community support – and the general public and regulatory agencies deserve to know what CAER does in its facilities, and to be assured that it's being done in a safe and appropriate manner. In these respects, EAs are welcomed and supported by the university. And, while in some cases EAs have led to project delays, in other respects they've improved the readiness of later projects - most recently with the addition of a Leed-Gold state-of-the-art 42,000 sq. foot laboratory. It has been well established through past EAs that most new buildings and facilities proposed for our research campus, which has been zoned and used for research, office and light industrial facilities for better than four decades will have no impact on the normal resource areas investigated in EAs (geological features; surface/ground water and floodplains; vegetation and wildlife; threatened and endangered species; or cultural resources, historical sites, or Native American reservations).

However, what's left and perhaps most valuable and important from our participation in EAs is to examine closely the specific processes and equipment that will operate, with respect to all their requirements from inputs to outputs of feed materials, to good product and waste streams, to ESH and hazards and operability [HAZOP]. In this instance, the EA Supplement for this facility encompassed the design, construction, and operation of the "upstream" components of the FT PDU Facility, specifically, the coal handling, gasification, and acid gas cleanup components. The EA examined the construction of associated equipment platforms and installation, and operation of the FT PDU Facility. The review covered the breadth of processes, equipment, feed and waste streams, accident scenarios and safety issues. Moreover, the assessment informed us about important considerations for maintaining the cordial relationships we've always enjoy with adjacent property owners and the community with respect to area proximity noise, odors and light-emitting sources, such as for example that related to the operation of a flare for the facility. All of this has been extremely valuable, albeit leading to delays in project implementation.

Professional A&E and Construction Management Services are Vitally Important

To assure that objectives of the project are met "on time" and "on budget", it's important to have in place a number of business and organizational procedures, resources, and tools. Essential procedures include implementation of a rigorous decision-making process, identification and engagement of the necessary participants for each phase of the project, and establishment of formal lines of communication and authority. During building and equipment design phases, there must also be mechanisms for verifying the completeness and accuracy of all design and construction documents. In the building construction and equipment fabrication phase, procedures need to be in place for strict control of the budget and of change orders. Finally, before the building and equipment are fully commissioned, hazards and operability must be fully understood, and shake-downs and pre-testing of the equipment and laboratory facilities is needed to assure that everything will operate safely and as planned.

With respect to the timely execution of this project, construction of the building utilized a Construction Manager at Risk project delivery model, with direct oversight by UK's Capital Projects Management Division. The project was logically organized and unified around three principal building phases: Task 1, Pre-design; Task 2, Design; and Task 3, Construction and Commissioning. Important subtasks of the project included: a.) Selection of the Design Team (A/E) and Construction Manager (CM); b.) Preparation/Approval of Schematic Design and Detailed Construction Documents; c.) Bid Package Preparation/Permits [for the building's foundation, steel, envelope, mechanical and equipment elements]; d.) Building Construction; and e.) Systems Commissioning. Professional A&E and construction management services were vitally important in bringing the building construction phase of this project in "on-time" and "on-budget".

<u>The Project Benefited Greatly from Strong Collaborations in China in the area of Coal Gasification</u>
Mention was made that the addition of coal gasification and related deep gas clean-up processes represented a fruitful field of future investigation and research for CAER – and an important syngas production facility for a variety of future and complimentary areas of research. And, while CAER has particularly strong and well respected capabilities related to combustion and emissions control, premium products derived from coal, and CTL/GTL catalysis to name a few, coal gasification represents a field in which CAER has little direct experience. Thus, this project benefited greatly from CAER's strong collaborations in China, and particularly with that nation's Key Laboratory of Coal Gasification at East China University of Science and Technology. In addition to designing and managing the fabrication of our research-scale gasifier [modeled after the many versions located at their labs and some 26 commercial deployments in China], ECUST personnel [visiting staff and faculty] have made outstanding contributions to the installation of the coal handling system and gasifier and we expect their assistance in shake-down and commissioning.

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